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TECHNICAL REPORT NO. 77-1239-1

CAPITAL INVESTMENT PROGRAM FOR MITIGATION OF RISKS FROM NATURAL HAZARDS

METHODOLOGY REPORT

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A general methodology for use in selecting an optimum capital investment program for a military activity or complex. It minimizes the risk of mission impairment and the risk of economic loss from damage to facilities as a result of disaster. It is a balanced program: it achieves where possible and beneficial, an equal level of protection from fire, flood, earthquake, and high wind. If the risk from any hazard is acceptable, it is not further considered.

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CAPITAL INVESTMENT PROGRAM FOR MITIGATION OF RISKS FROM NATURAL HAZARDS

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TABLE OF CONTENTS

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TABLE OF CONTENTS
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TABLE OF CONTENTS
(Continued)

TABLE OF CONTENTS
(Continued)

LIST OF FIGURES

LIST OF FIGURES
(Continued)

LIST OF FIGURES
(Continued)

PAGE

LIST OF FIGURES
(Continued)

LIST OF TABLES

LIST OF TABLES
(Continued)

PAGE

CHAPTER SEVEN (Continued)

1. OVERVIEW

1.1 Introduction

Past naval experience has shown that the construction and modification of structures and other facilities have included structural features and systems to reduce the risk of damage from natural disasters and fire. However, these special features have usually been chosen for individual disasters with no effort made to balance protection from all hazards. Moreover, decisions to incorporate special features in facilities have generally been made without specific knowledge of the benefits in mission continuation, protection of personnel, and avoidance of economic loss.

This document has been developed to provide a general methodology for the Navy to use in selecting an optimum capital investment program for a military activity or complex. This proposed methodology will, where possible, minimize the risk of mission impairment, and economic loss from damage to facilities as a result of disaster. Moreover, this investment program has been constructed to be a balanced one which achieves, where possible and beneficial,* an equal level of protection from fire, flood, earthquake, and high wind. If the risk from any hazard is already acceptable, that hazard will not be considered further.

The methodology permits the selection of different funding levels to meet budgetary restrictions, while equalizing the levels of protection from the stated disasters. For different funding levels, the methodology is also capable of identifying the benefits to be achieved in mission continuation, protection of personnel, and avoidance of economic loss.

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*See Section 1.6 for clarification.

The methodology considers or provides for the following specific matters in arriving at a capital investment program:

- Provides for a mission importance factor,
- Considers severity and probability of disaster occurrence,
- Classifies structures according to applicable factors,
- Predicts levels of damage,
- Provides general categories of mitigations,
- Discusses the monetary "value" of loss of life.

Sections 2 through 5 contain discussions on the fire, wind, earthquake, and flood hazards, respectively. In each section, the hazard, exposure, and damage methodologies are discussed. Section 6 discusses the methodology for an optimum capital investment program. This includes discussion on mission impairment and economic loss. A building inspection form is discussed in Section 7.

Appendices A through C contain information on the fire damage survey, the wind damage survey, and the inspection forms.

The work presented here was presented, in an abreviated form, at the 1976 ASCE Annual Convention and Exposition under the title "Engineering Risk Management of Natural and Man-Made Hazards" [1-7]. A paper entitled "Engineering Risk Management for Structures" has also been submitted to the ASCE for publication in the Journal of the Structural Division.

1.2 Acceptable Risk to Personnel

Any discussion of the risk of death and injury must address the question of acceptable risk. However, this question is of even greater importance here due to the inability to accurately quantify the effect of a specific mitigation on the casualty rate. In fact, even the quantification of the casualty rate itself requires much subjective and intuitive reasoning, as will be discussed later.

The life loss estimates for each hazard must be compared to the risk of death which the public faces from various causes. These risks are generally grouped into two categories[1-2]: those associated with voluntary activities and those associated with involuntary activities. Voluntary risks are those over which an individual has some control, such as those due to occupation and transportation. Here the individual tries to adjust his exposure, usually subconsciously, to obtain a level of risk acceptable to him.

Although each individual is different, there appears to be a general consistency in the average risk associated with accidents of various kinds. And this risk appears to represent a societal norm. In fact this rate, about 10^{-6} fatalities per person-hour of exposure, falls very close to the statistical rate of death from disease.

Involuntary or "uncontrollable" risks on the other hand, are those over which the individual has little or no control. Earthquake and windstorm are of this type. During the last forty years the public has become much more aware of these risks and is now attempting to control them through its legislative and regulatory bodies. Building codes with earthquake

design requirements, flood plain zoning, and hurricane modification are a few of the approaches being used. Starr[1-1] indicates that the public is only willing to accept involuntary risks roughly 1000 times smaller than voluntary risks. On this basis an acceptable level for involuntary risk would be 10^{-9} fatalities per person-hour of exposure[1-2].

1.3 Monetary "Value" of Human Life

The establishment of any kind of worldly value for human life is a sensitive topic, because the layman is frequently tempted to measure value in absolute terms rather than in relative terms. The absolute is meaningful only with reference to one's self. Otherwise, an individual can claim no absolute. Many valid approaches for relative valuation are conceivable, however, depending on what the objectives of the valuation are. No one can argue against the need for establishing a monetary value, for example, when the objective is monetary compensation for a lost life. Thus, the "value" established for a life is meaningful only with reference to its intended use; it is a relative value. This distinction makes it possible to valuate human injury and loss of life in an objective manner. The first step is to define the objective, the second is to define the unit of measure.

The placing of a monetary value on life can be traced back for over a thousand years. According to a recent study,

> One of the first evaluations of human life was made in the old Anglo-Saxon law and was variously called the wer, wergild, wite, or bøde. The value set on an individual was used in determining the compensation allowed to his relatives if he was killed by a third party and was based on his station in life. This bøde had to be paid by the person committing the homicide, and if he was unable to pay the amount of the bøde he was sold into slavery or exiled. . . . This estimate was based upon the wealth that he had accumulated during his life.[1-3]

Human values are generally used to equate life loss to economic loss. The expected casualties can then be added to the expected economic loss to provide a single parameter indicative of hazard impact. When the costs of the mitigations

necessary to reduce the loss are compared to the aggregated losses (life + economics), the resulting benefit/cost ratio provides a convenient tool for the decision maker. If the benefit/cost ratio is positive, he implements the mitigation; if it is not, he does not. In many cases, this decision will be sensitive to the value assigned to human life. This section presents several state-of-the-art approaches for developing human values.

The mitigation methodology presented here does not, however, include these human values. This is due to the inadequacy of casualty-rate data on a building-by-building basis. The number of casualties resulting from historic disasters is well known, on a regional basis. However, the effect of local design codes, building practices, warning times, organizational efficiency, pre-disaster planning, public attitudes, etc., on the number of casualties is not known.

These unknowns may not be critical when dealing with a large population base such as a single state or the entire country since local differences will tend to average out. However, this is not the case when dealing with individual buildings. Here the lack of local casualty-rate data (percent of exposed population killed or injured) for each intensity level precludes the determination of the benefit resulting from a mitigation. In fact, for most natural hazards the number of casualties depends much more on the warning and evacuation systems and on public understanding of the hazard than it does on the building mitigations.

The first approach presented here is one developed by Bob Buehler[1-4]. In his approach, the value of a human life is defined as the present worth of the lost lifestream of

earnings that would result if death or disability were to occur. He bases these loss earnings on the individual's worth to his family and society, although he only demonstrates the former.

The individual's worth to his family (next-of-kin concept) can be visualized by the married father situation. Usually the father's earnings are adequate for house and car payments and other family support. When this happy status is interrupted by death which can be blamed on someone else, the courts are likely to award to his family the equivalent of the lost stream of earnings that otherwise could have been expected. This can be equated to a present worth capital sum of money using an appropriate discount rate.*

The individual's worth to society (society-in-general concept) is obtained by noting that as a worker he is producing goods or services demanded by society. As a result of his death, society loses this production. The nearest measure of the worth of his production is his stream of earnings which can be equated to a present worth capital sum.

Based on the previous definitions, Buehler has compiled a table (Table 1-1) that provides human values based upon the following divisions: three adult age groups and retirees for married males, unmarried males, unmarried females, married females with and without children; and three age groups for male and female children. This totals 26 groups.

These values of lost life earnings are based on several factors. Whether or not this loss was due to death or disability is an

*The discount rate accounts for the generally accepted economic premise that future income is worth less today than when it will be earned.

VALUE OF LOST LIFE EARNINGS--DEATH (1971 DOLLARS) [1 - 4]

	Unmarried Males		Unmarried Females		Husbands		Wives without Children		Wives with Children			Male Children		Female Childre-	
Age (1)	Value (2)	Percent-age* (3)	Value (4)	Percent-age* (5)	Value (6)	Percent-age* (7)	Value (8)	Percent-age* (9)	Value (10)	Percent-age* (11)	Age (12)	Value (13)	Percent-age* (14)	Value (15)	Percent-age* (16)
Less than 25	196,490	2	137,880	3	228,430	6	125,730	3	365,230	3	3	74,600	3	71,200	3
26–40	204,920	3	106,830	4	237,508	12.5	113,331	3.5	246,041	9	12	132,300	10.5	128,300	10.5
41–65	140,690	1	69,750	1	168,840	7.5	79,400	6	79,400	1.5	17	169,000	1	164,000	1
Greater than 65	64,000	2.5	28,550	2.5		0		0		0	Weighted average	122,890	14.5	118,955	14.5
Weighted average	153,933	8.5	93,532	10.5	215,605	26	100,020	12.5	254,012	13.5					

*Percentage of sample.
Note: Composite value = 160,823.

VALUE OF LOST LIFE EARNINGS--DISABILITY (1971 DOLLARS)

	Unmarried Males		Unmarried Females		Husbands		Wives without Children		Wives with Children			Male Children		Female Childre-	
Age (1)	Value (2)	Percent-age* (3)	Value (4)	Percent-age* (5)	Value (6)	Percent-age* (7)	Value (8)	Percent-age* (9)	Value (10)	Percent-age* (11)	Age (12)	Value (13)	Percent-age* (14)	Value (15)	Percent-age* (16)
Less than 25	245,610	2	176,010	3	285,450	6	182,750	3	422,250	3	3	138,160	3	113,610	3
26–40	256,150	3	152,500	4	296,885	12.5	172,708	3.5	305,418	9	12	193,730	10.5	156,000	10.5
41–65	175,860	1	87,190	1	210,030	7.5	121,590	6	121,590	1.5	17	230,900	1	185,140	1
Greater than 65	80,000	2.5	35,690	2.5		0		0		0	Weighted average	184,789	14.5	149,239	14.5
Weighted average	192,415	8.5	125,233	10.5	269,192	26	150,581	12.5	310,955	13.5					

*Percentage of sample.
Note: Composite value = 208,725.

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Table 1 - 1.

important one. Others include earning trends, age, and life expectancy.

Also included in Table 1-1 are weighted averages for seven group combinations and the weighted composite of the entire sample.

Another approach was developed by H. P. Miller and R. A. Hornseth[1-5] for the Bureau of the Census. They define the value of a human life, like Buehler, as the present worth of lost earnings. Their figures are derived from published 1960 census figures for white and nonwhite men classified by age, education, color, and major occupation group. Since the figures are based on a cross-section of the population at a given point in time, they reflect the employment conditions, demand and supply of labor, occupational wage differentials, and other relevant relationships that existed at that time. Since these relationships change over time and since men change occupations (although it is assumed by Miller and Hornseth that they remain in the same major occupation group for a lifetime), it is likely that the estimates presented in this report differ from those that would be obtained from life-history data tracing a man's earnings from the time he starts to work until he retires.

The basic method used by Miller and Hornseth to prepare the estimates is based on a formula which includes the following parameters: the average (mean) annual earnings, the average number of survivors, the annual increase in earnings due to rising productivity, and an appropriate discount rate. In addition, a factor, which is subtracted from the initial estimate of present worth, is derived to account for the cost of maintenance for the individual worker.

A third approach, developed for the Committee on Cumulative Regulatory Effects on the Cost of Automotive Transportation [1-6], is less general than the two previously presented. It was developed specifically to be used in a cost-effectiveness program to weigh the benefits of new safety equipment for automobiles. The figures were based on average traffic fatalities, making no discrimination between sex, age, or race. It was assumed that the average traffice fatality caused the victim to forfeit 36.9 years of life. By multiplying the forgone years of life by the per capita income, a figure of $139,703.40 per U.S. traffic fatality was derived. Therefore, if a dollar value based on value awards for accidental loss of life were needed, this value could be used. However, other estimates of human value have been made in relation to automobile fatalities. These range from $44,000 to $300,000. The National Safety Council was responsible for the $44,000 figure; the Federal Aviation Administration for the $300,000 figure. An estimate of $200,000 was made by the National Highway Traffic Safety Administration.

As one can see, there exists a wide variance in valuing human life. As a result, caution must be used in selecting the figure to be used. The following provides a guide to help in selecting the appropriate figure:

> When values are to be used as benefits, extension to achieve low values would provide conservatism. When values are to be used as risks, the opposite technique would be conservative.[1-4]

These approaches are few among many. And, understandably, the many different approaches result in some confusion about how much a human life is worth. In any event, it should be reemphasized that these values should not be used unless absolutely necessary. This not only due to lack of agreement on

the worth of human life, but mainly due to inadequate casualty-rate data as will be discussed later.

1.4 Determination of Risk

The process of computing risk can be separated into a series of steps:

- the hazard model,
- the exposure model,
- the vulnerability, and
- the damage algorithm.

These steps, shown graphically in Figure 1-1, are but a portion of the entire mitigation methodology being described herein.

The hazard is that phenomenon of nature (or man in the case of fire) which produces potentially destructive conditions. The hazard model is a probabilistic description of the hazard including its probability of occurrence, location, and severity. Both regional conditions, such as weather patterns, and local conditions, such as ground elevation, go into the formation of the hazard model.

The exposure model is a mathematical description of man's assets which are subject to damage from the hazard. This description may be in terms of the replacement value ($), the number of people present, or the structure's importance as reflected in a mission network. The vulnerability, in turn, describes how sensitive the assets are to damage. A poorly built or designed structure will have high vulnerability; a well designed and built one will, on the other hand, tend to have low vulnerability. Content vulnerability is also important. This, however, depends basically on the fragility of the item with respect to a specific hazard. Items may be insensitive to one hazard but highly susceptible to another.

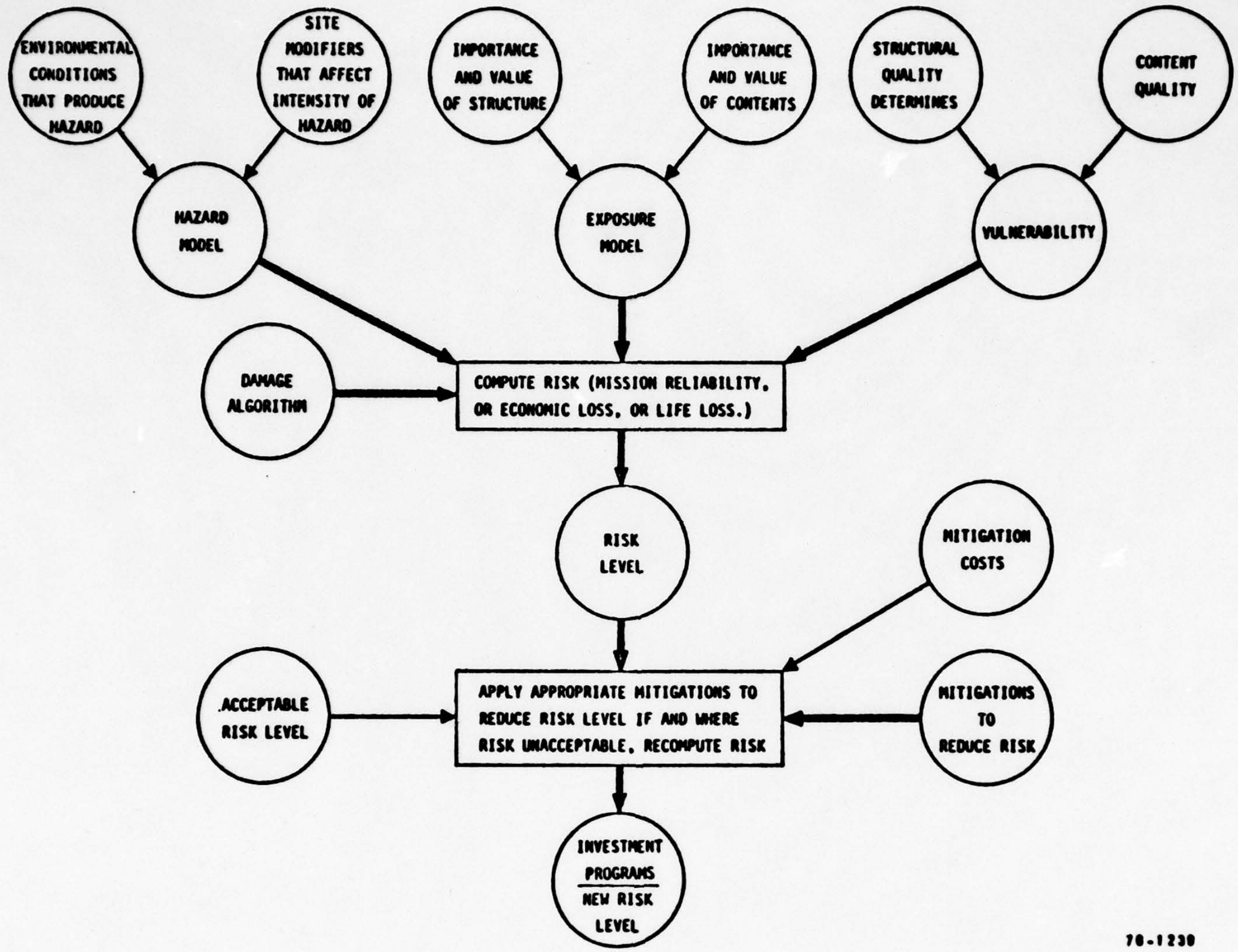


Figure 1-1. The Decision Process in Risk Evaluation

The damage algorithm is a relationship which predicts damage to the exposed assets. The degree of damage will depend on the hazard intensity and the vulnerability of the assets. The risk equation relates all four elements resulting in a quantification of the risk level. This quantification may be in terms of mission reliability, expected average annual economic loss, or expected casualties. The final criterion, casualties, is not recommended for this evaluation.

When the baseline level of risk is determined, a comparison is made to the acceptable risk level. The acceptable risk is that level of risk below which no specific action by the Navy or Marine Corps is deemed necessary. If the risk is unacceptable, mitigations must be applied. The sequence of implementing the mitigations depends on their cost and their benefit (i.e., the amount of risk reduction).

Before proceeding with the presentation of the risk reduction methodology, a discussion of the difference between deductive and inductive risk analysis is required. Deductive analysis is that process whereby data are gathered from former events and used as a basis for the prediction of structural performance in future events. This is the most common procedure used in the insurance industry; tables are developed based in mortality, structural losses, and accidents and then projected forward to form the basis of rates for occurrences in the future. Deductive analysis requires a very large body of data on similar types of occurrences. If such data are not available, the deductive process breaks down. Good examples are found in the space program where launches are often the first of a kind and there is no experience to establish a failure rate with high confidence. Hence, in those areas where the data are very

limited, the deductive analysis has to be replaced with an inductive analysis which uses mathematical models based on known structural behavior to predict what will happen in the future. Inductive models have been the standard means by which companies in the aerospace industry have predicted risk.

Lack of deductive information is not unique to the aerospace program, however, The earthquake data that are currently available represent a very small time sample in a random process. Consequently, this short period of data, spanning no more than 40 years, does not provide a complete picture of the frequency and magnitude of earthquakes which can occur throughout the United States or the world. Deductive analysis of earthquake data can only be truly effective when the time base of the data ranges over more than 400 to 1,000 years. Consequently, the use of inductive analysis is a necessary step in quantifying the earthquake hazard. The state of the art in earthquake engineering has, however, not quite reached this stage. Consequently, the earthquake model used here (Section 4-2) still remains a deductive one. Other natural hazards such as tornadoes and hurricanes have a higher frequency of occurrence than earthquakes and therefore, a deductive analysis of the hazard is of greater validity.

Figure 1-2 pictures typical procedures for the computation of risk from earthquakes and wind. As seen in the figure, there are two paths in the computation of the wind risk. The deductive path, which makes use of actuarial data for the damage algorithm, and the inductive path which involves the modeling of the structure and the use of synthetic damage algorithms to predict the damage levels. The methodology being presented here uses the deductive damage algorithms even though the data base is very limited in some cases. The amount of effort

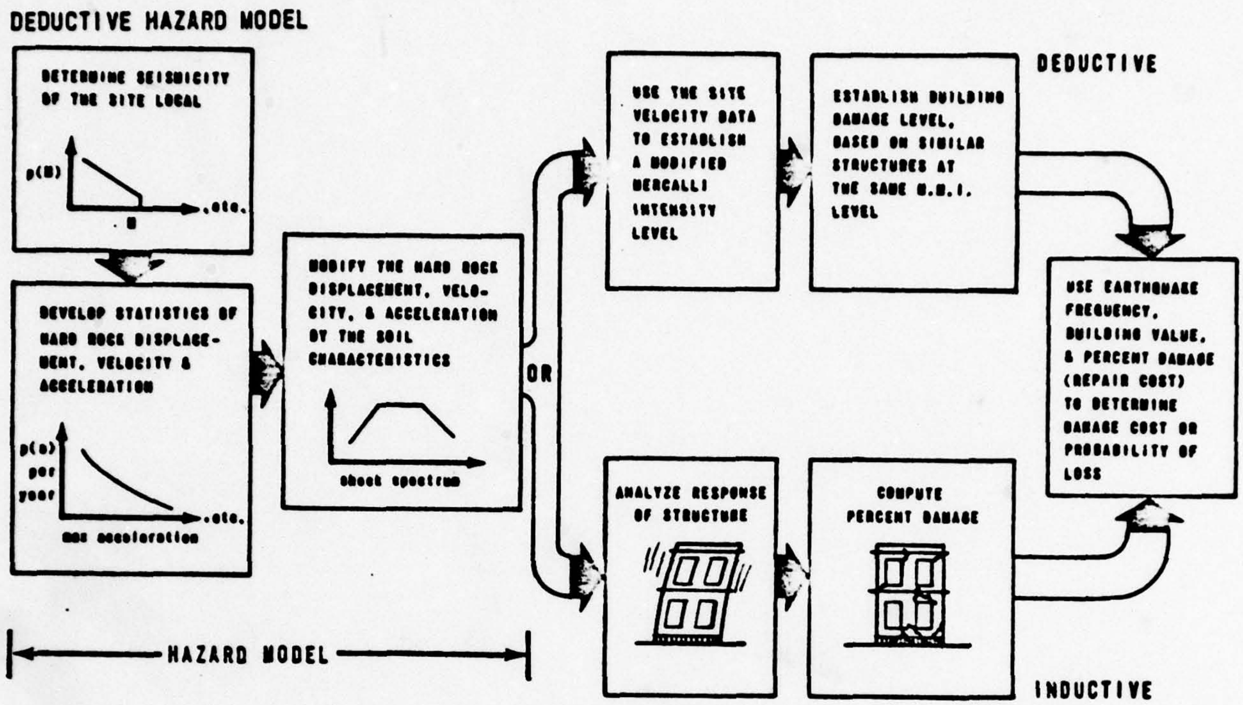


Figure 1-2a. Computation of Earthquake Risk

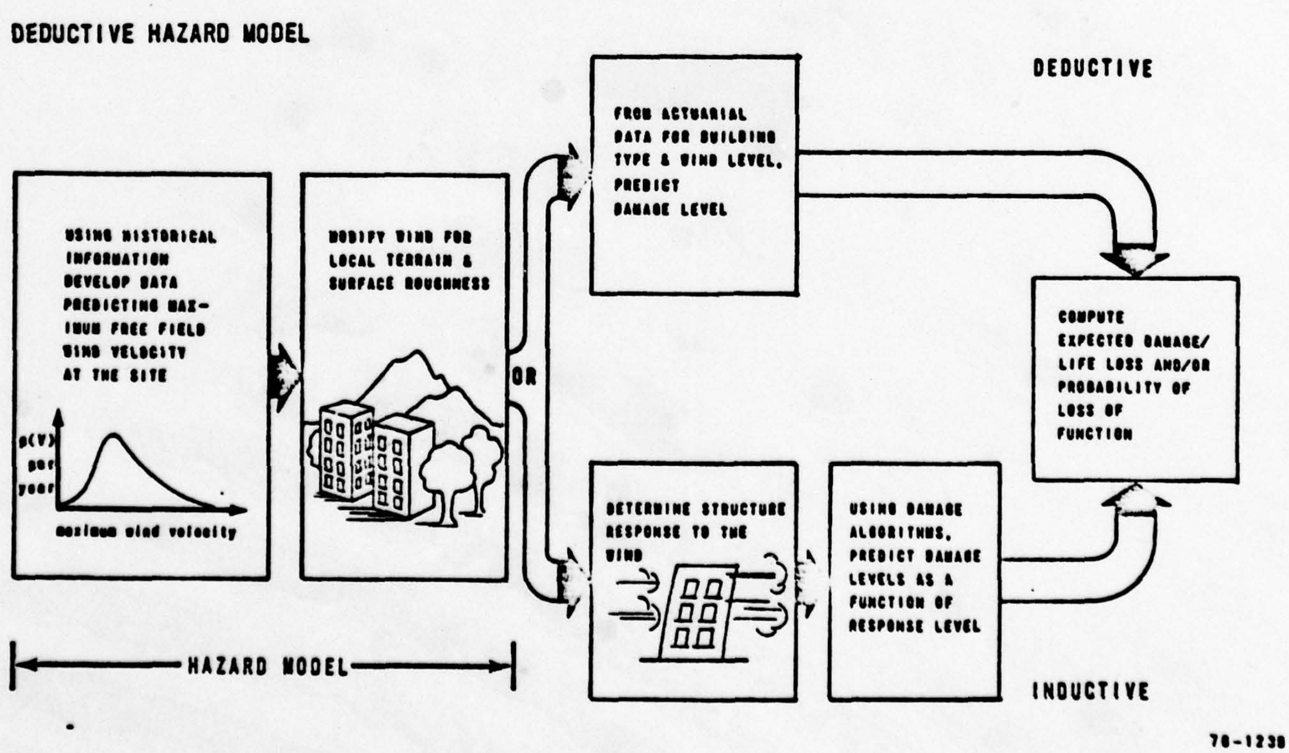


Figure 1-2b. Computation of Wind Risk

required to develop inductive damage algorithms for a wide range of building types would be immense even for those hazards for which development would be possible. In addition, some hazards, particularly fire, are not well enough understood yet to even develop such algorithms.

30

1.5 General Methodology to Produce an Investment Program

The general methodology is described in Figures 1-3a and 1-3b. This flowchart illustrates the logical process with which an optimum capital investment program can be selected for a military activity. The criteria for selection insures that the risk of mission impairment and/or economic loss from damage to facilities is minimized. Life loss and injury can be considered if this is required. In addition, the methodology is constructed so as to achieve, where possible, equal levels of protection from fire, earthquake, flood, and high wind.

The methodology initially requires the acquisition of certain data. Basically, these data are made up of six types: hazard, damage, vulnerability, exposure, mitigations, and cost.

The type of data required to define the hazard usually comes in the form of a frequency relationship, where the average number of events per year or the return time of an event of specified intensity is determined. Some of these data are provided by the base master plan or by the public works office. Some additional data are incorporated directly into the methodology.

The building inspection form provides the basic source of vulnerability data. This information is used to quantify the vulnerability of the structure from each of the four hazards. Information, such as structure age, construction type, and current level of fire protection is included.

To obtain exposure data, information from the base property control offices and the public works office is utilized. This includes the number of occupants in each building, the value of the contents of each building, and mission functions of each building.

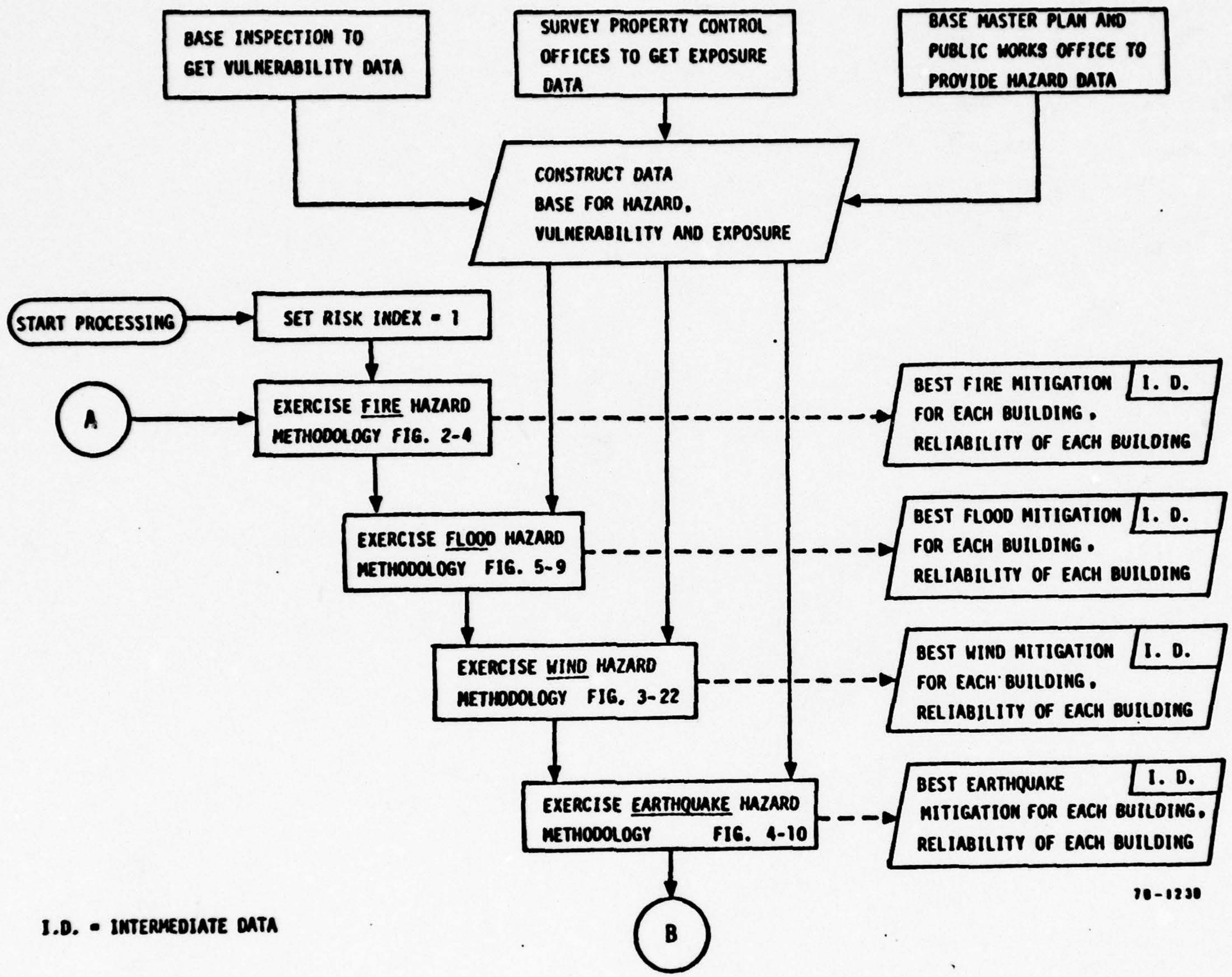
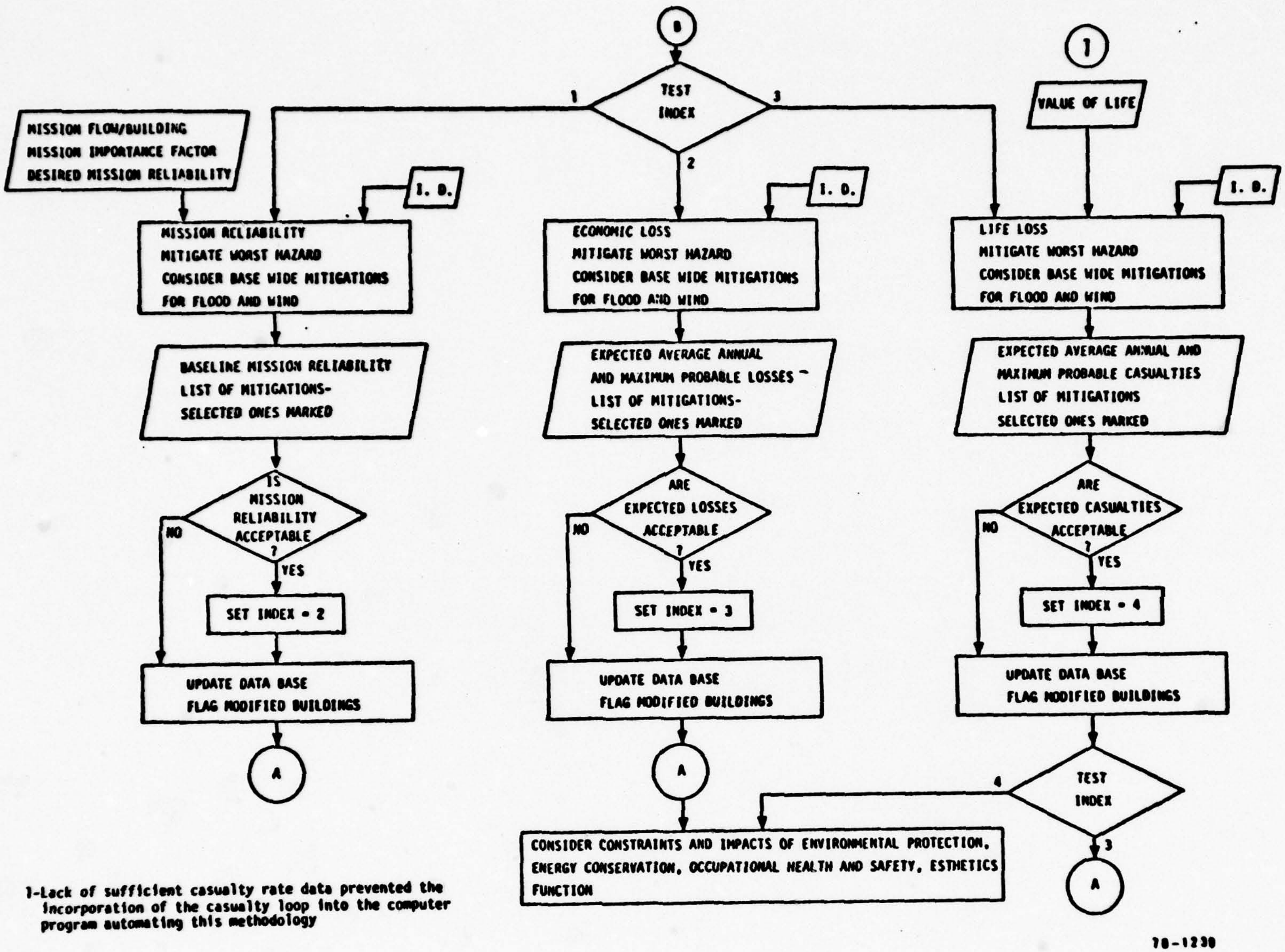


Figure 1-3a. General Methodology



1-Lack of sufficient casualty rate data prevented the incorporation of the casualty loop into the computer program automating this methodology

Figure 1-3b. General Methodology

Once the basic data is compiled, the methodology is initiated by setting the index to 1. This index indicates which of the three criteria (mission loss, life loss, economic loss) is being considered. Index 1 corresponds to mission impairment while Indices 2 and 3 correspond do life loss* and economic loss, respectively. The output produced for each criterion is given in Table 1-2 (page 1-23).

The next step consists of exercising the different hazard methodologies. The operations within this block will be discussed in subsequent sections for all hazards. The important point to be noted here is that through a benefit/cost type of analysis, the best mitigation applicable to each hazard is provided for every structure. In addition, an estimate of the structure's initial level of reliability is provided.

For Index 1, risk of mission impairment, a mission importance factor can be introduced. This factor has been implemented using two different approaches. The first approach orders the missions in terms of most important to least important. The missions are then considered in that order when all applicable mitigations are applied. The second approach utilizes a weighting factor. This factor ranges from 0 to 1, where 1 is applied to the most important mission. The benefit/cost ratios of the missions are then multiplied by these factors to produce an index that one could use in assessing the relative importance of each mission. Each mission must also be assigned a mission reliability. This number will reflect a decision on the part of the Navy as to what reliability is deemed acceptable for a particular mission.

Once the mission and its component structures have been determined, the next step involves selecting that hazard which

---

*Due to lack of data on the effect of various mitigations on casualties it was not possible to incorporate the life-loss methodology into the computer program developed under this contract.

contributes most to mission impairment. Figure 1-4 illustrates a typical breakdown of mission risk defined in terms of the reliability of the system. Each hazard has an initial level of reliability. An acceptable level of mission reliability is obtained when all hazard reliabilities are acceptable; that is, when all bars in Figure 1-4 are at or above the dotted line.

The first step in attaining equal protection from all hazards is to select that hazard which is most critical. Once this is done, mitigations are implemented until a level of reliability equal to that of the next critical hazard or an acceptable level is attained. The mitigation selection is based on a system benefit/cost analysis. A complete description of the process is given in Section 6.

After the required mitigations have been implemented the total mission reliability is examined to see if it is at an acceptable level. If it is, the index is set to two and the methodology proceeds to consideration of economic loss.

If the reliability is not acceptable, we select the worst hazard, proceed back to A to exercise the hazard methodology. We then implement mitigations to bring the reliability of that hazard up to that of the next hazard or the acceptable level, whichever is lowest.

Two points must be made. First of all, whether or not the mission reliability is at an acceptable level, we must update the data base as well as flag modified buildings. The reason for this is that once a mitigation has been added it immediately changes the level of protection from all hazards. That is, if we considered the risk due to earthquakes first and implemented the applicable mitigations, the structure would be modified and possibly would have a higher resistance to other hazards such

Table 1-2. Summary of Output

MISSION RELIABILITY
• List of structures and mitigations ranked in order of least reliable hazard mitigated first and within each hazard in order of decreasing benefit/cost.
EXPECTED DAMAGE
• List of structures and mitigations ranked in order of decreasing benefit/cost ratio.
LIVES LOST OR PERSONAL INJURY
• List of structures and mitigations ranked in order of decreasing benefit/cost ratio (not implemented).

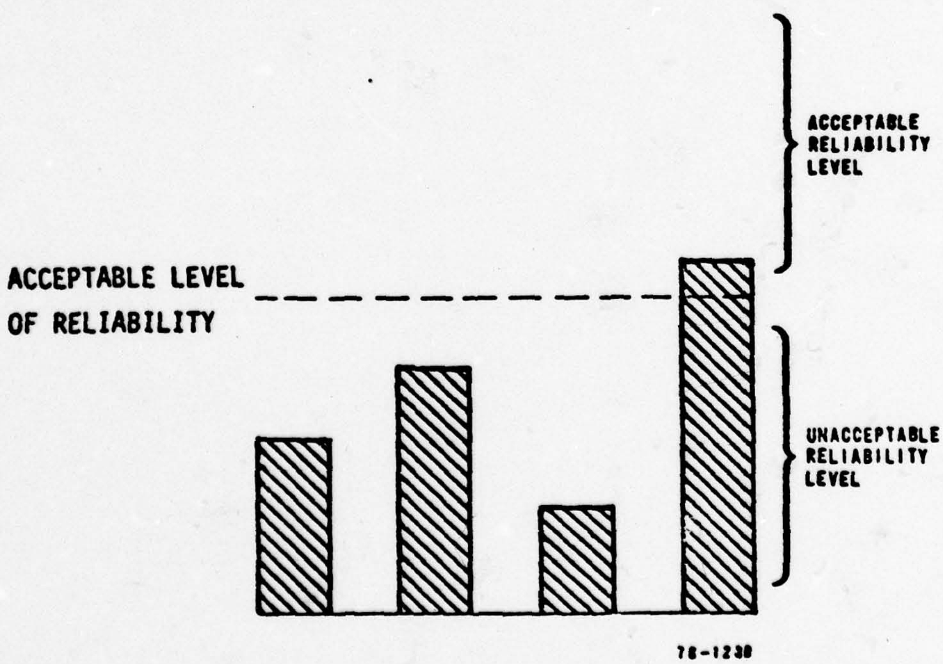


Figure 1-4. Mission Reliability by Hazard

as wind. Therefore, in selecting any mitigation, we must also carry the effect of adding it through all hazards.

The second point concerns the selection of the next hazard if the mission reliability is not acceptable. Since on the first iteration the reliability of the most critical hazard was brought up to level of the next, we might have two hazards with the same effect (i.e., same reliability). To determine which of the two should be selected a criterion that enables us to make this decision optimally has been incorporated. The criterion utilizes benefit/cost ratios. Since both levels are equal, the increase in reliability needed to the acceptable level is the same for both. Therefore, the most economical series of mitigations determine which hazard will be selected. Once the appropriate hazard is selected, the same process as was used for the first hazard is applied. When all reliabilities are at an acceptable level or when all possible mitigations have been added, the methodology proceeds to risk index two.

An additional point must be made with respect to mission reliability. When the reliabilities of each of the hazards reach the acceptable level, an aggregated mission reliability can be calculated.

$$\text{MISSION RELIABILITY} = \prod_{j=1}^{4} R_j \qquad (1\text{-}1)$$

where

j = hazard index

1=Fire
2=Wind
3=Earthquake
4=Flood

R_1 = reliability of mission due to fire

R_2 = reliability of mission due to wind

R_3 = reliability of mission due to earthquake

R_4 = reliability of mission due to flood

The above formulation of total mission reliability implies that the hazards are independent and that failure from only one hazard is necessary to deactivate the mission.

To illustrate the process of estimating total mission reliability, an example is given below.

Assume that the reliability of each of the hazards has reached the acceptable level and that each is equal to 90 percent. This implies that if each hazard is considered separately, the mission would have a probability of 90 percent of surviving a given disaster. However, if the reliability of the mission due to all hazards is to be estimated, Equation (1-1) will be utilized.

For this example base, the aggregated mission reliability would be

$$\text{MISSION RELIABILITY} = (.90)^4$$

$$= .656$$

1.6 Balanced Risk versus Optimum Investment Program

The prior methodology produces a program that is optimal in the sense that it insures equal or satisfactory protection from all hazards. It may not, however, produce the most optimal program from the standpoint of total mission reliability. That is, the methodology developed herein does not mitigate the hazard which gives the largest benefit/cost ratio but rather selects the hazard that is most critical (i.e., the one with the lowest reliability). For example, assume that the four hazards (fire, wind, earthquake, and flood) possess these respective reliabilities: 0.70, 0.55, 0.80, and 0.75. Also assume that the following benefit/cost ratios correspond to increases in reliability of 20 percent for the respective hazards: 0.20, 0.15, 0.10, and 0.15. The methodology used herein requires that the mitigations for wind be implemented first, because wind has the lowest reliability, 0.55. The other optimizing procedure would, however, implement the mitigations for fire first, because this has the largest benefit/cost ratio, 0.20.

It is inconsistent to have an optimum capital investment program in the sense of optimizing the benefit/cost ratio while still insuring equal levels of protection from each individual hazard. However, if all hazards are allowed to reach the acceptable level, the two approaches produce the same result. It is when budgetary restrictions prevent bringing all of the hazards up to the acceptable level that the two approaches may differ. For example, if the investment program were halted due to budget constraints, the approach used herein would produce a program that would provide for equal levels of protection from the most critical hazards. The other approach, however, would produce a program which insures

that the spender is obtaining the most benefit for the money spent.

If an acceptable level were not required, an optimum capital investment program could produce results that may not be balanced and that may not be acceptable on an individual hazard basis. It is for the previous reasons that we have selected the methodology that would insure equal levels of protection. (Note: These levels are attained in the most optimal manner.)

1.7 References

1-1 C. Starr, "Social Benefit versus Technological Risk," Science, 1969.

1-2 J.H. Wiggins and D.F. Moran, "Earthquake Safety in the City of Long Beach Based on the Concept of Balanced Risk," J.H. Wiggins Company, September 1971.

1-3 A.E. Hofflander, "The Human Life Value: An Historical Perspective," J. Risk and Insurance, 381-391, September 1966.

1-4 R. Buehler, "Monetary Values of Life and Health," J. Hydraulics Division, 29-47, January 1975.

1-5 H.P. Miller and R.A. Hornseth, "Present Value of Estimated Lifetime Earnings," Technical Paper 16, Bureau of the Census, U.S. Department of Commerce, U.S. Government Printing Office, 1967.

1-6 W. Hoffer, "What Price is Right for Human Life?", Prism, 13, August 1974.

1-7 L.T. Lee and J.D. Collins, "Engineering Risk Management of Natural and Man-Made Hazards," ASCE Fall Convention and Exposition, Philadelphia, September 27 - October 1, 1976.

2. FIRE HAZARD

2.1 Introduction

The methodology developed for the evaluation of the fire hazard mitigations is discussed in this section. The salient features of the approach are summarized in Table 2-1. A flow chart of the risk calculation is shown in Figure 2-1. As with all four hazards, the methodology is broken down into six categories.

- Hazard Model
- Damage Algorithm
- Exposure
- Vulnerability
- Mitigations
- Costs

The hazard model was developed specifically for this project using naval fire and inventory data for the last seven years. The details of this model and the procedure used to develop it are discussed in Sections 2.2 and 2.3.

The fire damage algorithm was also developed specifically for this project using a modified Delphi survey technique. Although controversial, this technique permits the quantification of the needed parameters in the absence of the normally required statistical data. The details of this damage algorithm are given in Section 2.4. The survey results are reported in Appendix A.

The exposure data is that information required to determine the type and quantity of assets (economic, personnel, mission)

Table 2-1. Information Requirements for Fire

HAZARD AND DAMAGE	DATA SOURCE
Hazard Model	
Fire Probability (Based on Occupancy) Proportional to Floor Area	Developed In-House (Based on Navy Data)
Structural Damage and Contents Damage	
Probability Damage Matrices ● No Protection ● With Detection System ● With Automatic Sprinkler System ● Both Detection and Sprinkler Systems	Survey of Experts
Life Lost	
Casualty Rate	Lacking (Not Incorporated)
Mission Reliability	
Damage Level Assigned to Mission Failure	Assigned (Building Failed if Damage Exceeds 50% to 1 fire area)
EXPOSURE AND VULNERABILITY	**DATA SOURCE**
Building	
Structure Age	Class 2 Property Inventory
Type of Construction ● Fire Resistive[1]* ● Non-Combustible[2] ● Ordinary Wood Frame[3]	Base Inspection
Floor Area, Number of Stories	Property Inventory
Building Surface Area	Estimated
Interior Finish ● Non-Combustible [NC] ● Combustible [C]	Base Inspection
Fire Load (Based on Occupancy) ● Light ● Moderate ● Severe	Base Inspection

*Items in brackets key this table to flow chart on page 2-41.

Table 2-1. Information Requirements for Fire (Continued)

EXPOSURE AND VULNERABILITY	DATA SOURCE
Building (Continued)	
Current Level of Protection	Base Inspection
• None [NONE]	
• Fire Detection System [D]	
• Automatic Sprinkler System [S]	
• Both Fire Detection and Sprinklers [BOTH]	
Number of Fire Areas	Base Inspection
Type of Occupancy	Property Inventory
• Property Inventory Category Codes	
Value of Contents	Property Control Offices
• Class 3 and 4 Property	
• Inventory Material	
• Minor Property	
• Exchange and Commissary Property	
• Special Services Property	
• Surplus Property	
• Other	
MITIGATIONS AND COST	**DATA SOURCE**
Cost Data	
Construction Costs	
• Replacement Cost for Existing Structure	Property Inventory
• Original Cost for Proposed Structures	
Mitigation Cost Factors for Proposed Structure	
• Adding a Fire Detection System	MCCED, 1973
• Adding an Automatic Sprinkler System	MCCED, 1973
• Fireproofing	BCF, 1972
Mitigation Cost Factors for Existing Structure	
• Adding a Fire Detection System	MCCED, 1973
• Adding an Automatic Sprinkler System	MCCED, 1973
• Fireproofing	BCF, 1972
Geographic Cost Factors	
• Continental United States	MCCED, 1973
• Territories and Possessions	MCCED, 1973
• Foreign Countries	MCCED, 1973

MCCED = Military Construction Cost Engineering Data[2-14]
BCF = Building Cost File[2-15]

that are exposed to the hazard in each structure. This information must be assembled before any meaningful benefit/cost analysis can be performed. Since the same data are required for all four hazards, a single discussion of the acquisition of exposure data is presented in Section 7.

The vulnerability data is information required by the hazard model for determination of the expected damage. A special inspection form has been developed to collect this information (Section 7). The mitigations are discussed in Section 2.6, along with the methodology used to determine the best mitigation for each building.

Although all the terms have not yet been explained, a flow chart showing the steps involved in determining the risk from fire is presented in Figure 2-1. This figure may be a helpful roadmap to the following discussions of hazard, damage, and risk.

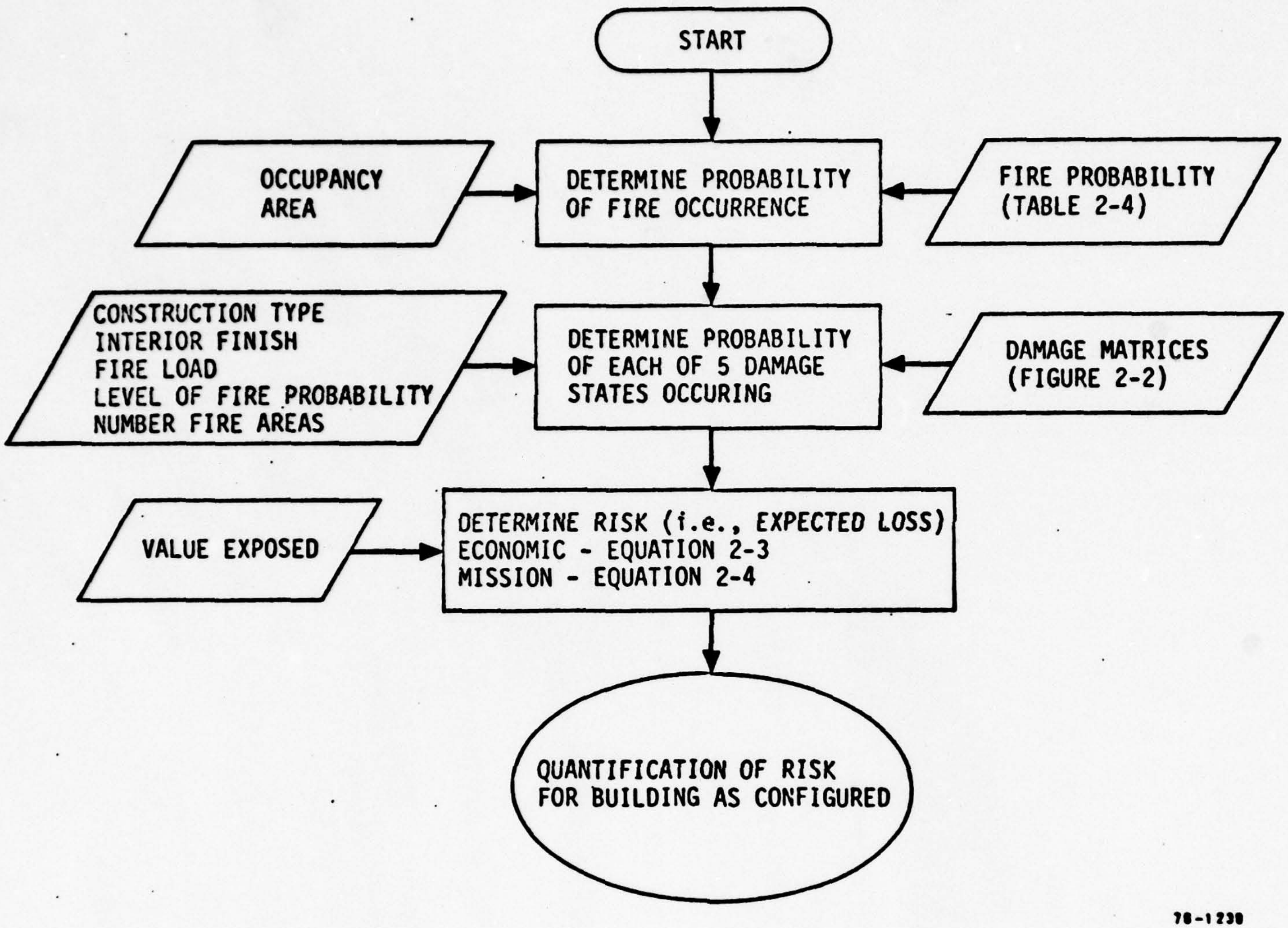


Figure 2-1. Calculation of Risk From Fire Hazard

2.2 Hazard Model

The occurrence of fire in a building may be considered a relatively rare and random event, much like the occurrence of an earthquake or a flood. Such events are often represented as a Poisson process implying the following three conditions [2-1]:

- The process is stationary. The probability of an event in a short interval of time, Δt, is approximately equal to $\lambda \Delta t$ where λ is the average number of events per unit time.
- The events are nonmultiple. The probability of two or more events in a short interval of time is negligible compared to $\lambda \Delta t$.
- The events are independent. The number of incidents in any interval of time is independent of the number in any other interval of time.

For such processes, the probability of occurrence of ν number of fires in time t is

$$P_f(\nu) = (p_m t)^{\nu} \frac{e^{-p_m t}}{\nu!} \tag{2-1}$$

where p_m is the mean number of fires per year in the subject building. This type of probabilistic formulation of the occurrence of fire allows one to average implicitly and otherwise ignore any cyclical fluctuations in the mean rate of occurrence, p_m, of fires with the season of the year, the

day of the week, or the time of the day. This is so because the observation time upon which p_m is based is very long compared to these possible cyclical variations and because we are not concerned here with any mitigation affected by this variation. The major reason, as stated by Burros, for the assumption of a Poisson process over a long time period is that the Poisson process is the simplest possible mathematical model for the generation of random events. Unless there is strong evidence that requires a more complicated model, this simplicity justifies its assumption [2-2]. As of now, evidence requiring a more complex model does not exist.

Lie postulates that for buildings with a large number of equal size compartments [2-3], $p_m = p_i A$, while Burros extends the same relation to buildings with any number of unequal size compartments[2-2].

- p_i is a constant for a population of buildings with varying total floor area. It measures the mean number of large fires per unit area per unit time. Thus like p_m, p_i is not a probability.
- A is the total floor area of the building in question.

Lie's paper [2-3] forms the mathematical basis for the last chapter in his recent book [2-4]. A comprehensive review of the literature on fire in buildings is given in that book [2-4] as well as in one by Marchant [2-5].

All that remains to complete the fire hazard model is to quantify p_i. This will be done in the next section.

2.3 Frequency of Fires

The parameter p_i prescribes the mean number of fires per unit area per unit time for a population of buildings. It seems reasonable that p_i will depend primarily on the type of occupancy and not be influenced by the type of building construction or the level of fire protection in the building. Certainly, the type of construction and level of fire protection can be expected to influence the amount of damage caused by a fire but they are not expected to have much effect on the chance of a large (i.e., a loss fire by Navy standards*) one occurring. Miller, Krasner, and Wiener[2-7] demonstrate this single dependency in their "Occupancy Rating Guide" which defines a fire frequency rating dependent only on occupancy.

The fire-frequency-rating scale defined in the aforementioned reference[2-7] provides three ranges for p_i:

RATING	DEFINITION	p_i - FREQUENCY NO. FIRES/SQ. FT/YEAR
1	Low Frequency	Less than 1×10^{-6}
2	Medium Frequency	1×10^{-6} to 3×10^{-6}
3	High Frequency	Greater than 3×10^{-6}

These ratings, however, are based primarily on industrial data and may not reflect Navy fire experience. Therefore new values of p_i are determined independently for as many Naval occupancy types as possible. The fire occurrence

*A no loss fire by Navy standards[2-6] is one with loss less than $1.00. This value is so low that any effect of construction on amount of loss could have only minimal effect on the number of fires reported.

data have been taken from Navy and Marine Corps Fire Loss Experience (Ashore) reports[2-8] and the corresponding real property data from the Inventory of Military Real Property[2-9]. Seven years of data with 10,613* loss fires have been used.

The fire occurrence data is summarized in Table 2-2 for the seven years used in this study. The occupancy classifications used for fire reporting[2-6] provide the classifications used in this table. The real property data is summarized in Table 2-3 for the same period. Many of the fire-frequency categories as well as the property categories have been combined for reasons to be discussed in Section 2.7. The resulting building populations for which a fire frequency, p_i, has been determined is given in Table 2-4. This is accomplished by aggregating fire occurrences from Table 2-2 with the aggregate areas from Table 2-3 according to the following equation for p_i:

$$p_i = \frac{N_i(1969) + \dots + N_i(1975)}{A_i(1969) + \dots + A_i(1975)} \qquad (2\text{-}2)$$

where

p_i = No. Fires/sq.ft./yr. for ith group (i.e., population)

$N_i(xxxx)$ = Total no. of fires in ith group during year xxxx

$A_i(xxxx)$ = Total area of ith group at end of year xxxx in square feet

Table 2-3 only provides floor areas according to the three digit category code defined in Reference[2-10]. This is the most detailed breakdown that is available for prior years[2-9].

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*931 of these fires were, however, inapplicable to the study at hand.

Table 2-2. Occurrence of Loss Fires at Naval Facilities 1969 - 1975 (Reference 2-8)

FIRE FREQUENCY CODE	TYPE OF PROPERTY	NUMBER OF FIRES BY YEAR							TOTAL
		1969	1970	1971	1972	1973	1974	1975	69 - 75
1	AEROSPACE MANUFACTURE, ASSEMBLY, AND MODIFICATION	18	18	16	12	10	14	11	99
2	AUTO GAS SERVICE STATION	1	-	6	1	1	1	2	12
3	BARRACKS	387	346	381	412	546	612	607	3,291
4	BUILDINGS, VACANT	6	4	9	16	18	13	21	87
5	BOQ'S	22	33	23	18	19	13	10	138
6	CAFETERIAS	6	6	3	5	6	3	7	36
7	CHILD CARE CENTERS AND NURSERY	-	2	-	2	1	2	-	7
8	CHURCH, CHAPELS	2	3	7	5	2	4	2	25
9	CLUBS-CPO	5	6	6	10	5	3	2	37
10	CLUBS-EM	16	16	19	8	5	7	13	84
11	CLUBS-OFFICERS	10	10	8	8	7	2	5	50
12	COLD STORAGE AND/OR REFRIGERATION PLANTS	2	2	1	-	-	1	3	9
13	COMMUNICATIONS	21	20	17	21	15	14	15	123
14	DISPENSARIES/DENTAL CLINICS	13	14	15	7	7	19	14	89
15	DRYDOCKS	1	-	1	6	1	2	7	18
16	DWELLINGS-DUPLEX	90	88	76	69	56	58	59	496
17	DWELLINGS-MULTIFAMILY	160	140	146	128	152	127	128	981
18	DWELLINGS-SINGLE FAMILY	125	76	91	96	111	103	132	734

Table 2-2. Occurrence of Loss Fires at Naval Facilities 1969 - 1975 (Reference 2-8) (Continued)

FIRE FREQUENCY CODE	TYPE OF PROPERTY	NUMBER OF FIRES BY YEAR							TOTAL 69 - 75
		1969	1970	1971	1972	1973	1974	1975	
19	DWELLINGS-TRAILER	11	10	12	7	9	4	9	62
20	ELECTRONIC DATA PROCESSING	-	3	1	2	3	5	6	20
21	ENGINE TEST CELLS	4	2	4	1	4	2	2	19
22	FLAMMABLE LIQUIDS/GASES-HANDLING AND/OR STORAGE	11	2	4	1	2	3	7	30
23	GARAGE (DWELLING)	6	4	6	11	2	6	8	43
24	HANGERS	16	12	11	15	7	8	25	94
25	HOSPITALS-OTHER THAN WARDS, SURGERY	16	20	9	14	12	7	17	95
26	HOSPITALS-WARDS	47	38	22	10	12	19	8	156
27	KNOWN, BUT NOT CLASSIFIED	40	70	114	55	50	98	67	494
28	LABORATORIES OTHER THAN MEDICAL	14	19	22	18	16	23	14	126
29	LAUNDRIES AND/OR DRY CLEANERS	5	6	2	5	8	7	9	42
30	MESS HALLS AND/OR GALLEYS	25	18	18	19	12	11	14	117
31	MANUFACTURING, PROCESSING, INDUSTRIAL	6	9	10	5	7	1	7	45
32	MISCELLANEOUS SMALL OUTLYING STRUCTURES	20	9	7	19	14	17	16	102
33	OFFICES, ADMINISTRATION, ETC.	61	49	70	59	68	76	73	456
34	MAGAZINE, ORDNANCE AND/OR CHEMICAL STORAGE	4	2	-	1	1	1	1	10

Table 2-2. Occurrence of Loss Fires at Naval Facilities 1969 - 1975 (Reference 2-8) (Continued)

FIRE FREQUENCY CODE	TYPE OF PROPERTY	NUMBER OF FIRES BY YEAR							TOTAL 69 - 75
		1969	1970	1971	1972	1973	1974	1975	
35	ORDNANCE MANUFACTURING, ASSEMBLY, AND MODIFICATION	92	44	50	40	40	30	24	320
36	OUTSIDE OR OPEN STORAGE	12	10	4	-	3	3	6	38
37	PIERS-WHARVES	24	9	12	15	8	15	7	90
38	POWER, HEAT, UTILITIES	40	21	27	27	29	28	29	201
39	PRISONER HOUSING AND DETENTION	2	4	6	2	5	3	4	26
40	RECREATION-GYM, ETC.	25	13	21	21	22	21	30	153
41	SCHOOLS-TRAINING	22	18	24	31	23	24	25	167
42	SHIPBUILDING WAYS	1	2	1	-	-	-	1	5
43	SHOPS, HOBBY	5	2	2	1	2	-	1	13
44	SHOPS, MISCELLANEOUS	12	20	17	11	28	27	14	129
45	SHOPS, O AND R	12	7	3	2	3	-	-	27
46	SHOPS, PUBLIC WORKS	9	10	10	15	12	7	4	67
47	STORES, COMMISSARY, EXCHANGES	16	12	13	10	18	13	23	105
48	THEATERS	8	3	5	1	-	-	4	21
49	VEHICLES AND MOBILE EQUIPMENT	103	105	90	113	124	122	114	771
50	WAREHOUSES, STORE HOUSES, SUPPLY	35	32	41	35	27	40	43	253
	TOTALS	1,589	1,369	1,463	1,390	1,533	1,619	1,650	10,613

Table 2-3. Real Property at Naval Facilities for Selected Category Codes (Reference 2-9)

CATEGORY	UNITS*	TOTAL AREA							TOTAL
		1969	1970	1971	1972	1973	1974	1975	69 - 75
123	SF	36	36	34	30	---	8	20	164
125	SF	284	289	324	344	401	443	470	2,555
131	SF	3,983	4,042	4,176	4,241	4,092	4,488	4,704	29,726
133	SF	735	683	732	722	614	580	588	4,654
141	SF	3,860	6,465	6,245	6,050	8,005	8,971	9,294	48,890
142	SF	13	7	7	7	3	3	3	43
151	SY	2,577	2,573	2,461	2,371	2,372	2,268	2,287	16,909
152	SY	1,369	1,433	1,458	1,349	1,167	1,271	1,185	9,232
153	SF	**	3,942	**	**	4,413	4,436	4,543	30,334**
155	SF	##415†	##403†	##305	368	251	334	319	2,395
159	SF	##336†	##326†	##248	168	290	283	290	1,941
161	SF	36	2	2	2	4	3	2	51
171	SF	36,252	33,006	30,648	32,654	32,979	33,185	34,106	232,830
211	SF	33,531	33,117	31,301#	29,486	34,024	35,713	36,135	233,307
212	SF	1,147	1,105	1,112	1,175	1,516	1,528	1,612	9,195
213	SF	27,977	26,544	19,432	19,599	24,208	24,657	25,480	167,897
214	SF	8,135	8,167	8,242	8,493	8,727	9,039	9,196	59,999
215	SF	665	671	643	603	548	824	808	4,762
216	SF	2,749	2,706	2,729	2,861	3,258	3,154	3,209	20,666
217	SF	2,846	2,938	2,987	2,869	3,185	3,833	3,418	22,076
218	SF	3,961	3,914	3,733	3,763	4,065	4,211	4,136	27,783
219	SF	10,680	11,648	11,399	11,621	11,774	12,557	12,518	82,197
221	SF	9,522	8,448	8,319	7,646	7,436	7,716	7,706	56,793

*Units are in 1000's; SF = square feet; SY = square yards.

**P-77 values for 69, 71, 72 appear erroneous. Total based on average of remaining years.

#P-77 gave different value, since it seemed inconsistent with 70 & 72 values, 71 values assumed erroneous. Value shown interpolated from 70 & 72.

##Apportioned according to 72--75 data.

†P-77 has units of square yards for these elements. Assumed to be square feet instead.

Table 2-3. **Real Property at Naval Facilities for Selected Category Codes (Reference 2-9) (Continued)**

CATEGORY	UNITS*	TOTAL AREA							
		1969	1970	1971	1972	1973	1974	1975	
222	SF	3,593	3,680	3,709	3,713	3,718	3,775	3,716	25,904
223	SF	681	281	180	**275	369	369	401	2,556
225	SF	173	173	173	185	117	117	117	1,055
226	SF	4,977	4,969	4,845	4,065	3,959	3,812	3,812	30,439
227	SF	499	430	430	670	676	452	464	3,621
228	SF	811	774	370	422	10	22	22	2,431
229	SF	1,016	1,039	1,027	1,195	1,099	1,436	1,509	8,321
310	SF	18,643	18,675	18,681	19,099	18,903	19,587	20,164	133,752
421	SF	30,240	30,541	29,736	29,828	38,667	39,021	38,224	236,257
424	SF	---	---	---	---	34	35	31	#231
431	SF	3,226	3,183	1,463	1,546	2,827	2,316	2,167	21,821
432	SF	1,280	1,309	1,236	1,268	---	---	---	
441	SF	64,645	64,757	62,377	64,234	118,883	116,357	113,047	877,570
442	SF	71,759	71,327	66,413	63,771	---	---	---	
510	SF	8,245	8,558	8,291	8,291	8,466	9,311	10,106	61,268
530	SF	1,609	1,626	1,590	1,589	1,264	1,396	1,418	10,492
540	SF	1,051	1,064	1,090	1,072	1,073	1,064	1,076	7,490
550	SF	3,149	3,260	3,200	3,267	3,275	3,237	3,205	22,593
610	SF	40,112	40,534	39,548	40,753	42,625	42,344	43,030	288,946
620	SF	250	250	246	274	237	217	219	1,693
711	SF	108,070	108,395	105,409	107,545	110,093	111,868	118,952	771,006
712	SF	171	171	165	145	19	0	3	

*Units are in 1000's. SF = square feet.
**P-77 data appears erroneous. Interpolated from 71, 73 data instead.
#Used average for 73--75 for all seven years.

Table 2-3. Real Property at Naval Facilities for Selected Category Codes (Reference 2-9) (Continued)

CATEGORY	UNITS*	TOTAL AREA							
		1969	1970	1971	1972	1973	1974	1975	
714	SF	2,508	2,507	2,459	2,550	3,239	3,750	4,187	21,200
721	SF	5,276	5,270	4,937	5,380	50,640	53,874	56,410	
722	SF	52,665	52,792	50,310	52,931	13,925	10,123	7,414	457,774
723	SF	8,314	8,306	7,915	7,774	1,171	1,173	1,169	
724	SF	14,914	14,977	14,662	14,425	11,314	13,044	12,929	96,265
730	SF	9,471	8,735	8,561	8,942	10,090	10,791	10,944	67,534
740	SF	45,093	45,611	45,478	47,936	50,662	52,425	52,462	339,667
760 #	SF	---	---	---	---	---	#	67	#469
811	SF	2,036	2,045	1,738	1,941	1,873	1,875	1,844	13,402
812	SF	866	872	831	878	709	697	710	6,105
813	SF	---	---	---	---	144	195	203	
821 ##	SF	3,135	3,089	3,054	2,965	1,332	1,763	1,870	17,208
822	SF	---	---	---	---	---	21	24	45
823	SF	6	7	7	10	12	13	13	68
826	SF	---	---	---	---	70	73	74	217
831	SF	185	252	184	179	361	361	371	1,893
832	SF	114	113	123	123	130	125	130	858
833	SF	193	200	173	172	153	**159	**164	1,214
841	SF	538	530	492	515	533	**540	**546	3,694
842	SF	312	305	315	345	285	**290	**295	
844	SF	---	---	---	---	3	6	9	2,285
845	SF	---	---	---	---	40	40	40	
872 †	SF	174	174	11	17	---	6	19	401
890	SF	824	855	821	838	610	507	673	5,178

*Units are in 1000's. SF = square feet.
**P-77 data inconsistent with Ref. 2-11 and prior years. Ref. 2-11 data used.
#Values for 69--74 missing or questionable. Assume 75 value.
##Data used as is; change between 72 & 73 unexplained.
†Data questionable but used as is.

Table 2-4. Fire Frequency by Category Code

COMBINED FIRE FREQUENCY CODES*	COMBINED CATEGORY CODES*	NO. OF FIRES**	TOTAL AREA**	FIRE # FREQUENCY--P_i
1 Aerospace Manufacture, Assembly, and Modification	221-all Production--Aircraft--Bldgs 221-all Production--Guided Missiles--Bldgs	99	82,697	1.20×10^{-6}
2 Auto Gas Service Station	123-15 Land Vehicle Fueling--Filling Station Bldgs	12	164	7.35×10^{-5}
3 Barracks 5 BOQ'S 30 Mess Halls and/or Galleys 39 Prisoner Housing and Detention	721-all Troop Housing--Bachelor Enlist 722-all Bachelor Housing--Mess Facilities--Bldgs 724-all Bachelor Housing--Officer Housing--Bldgs 725-10 Troop Emergency Housing 730-15 Confinement Facility 740-60 Commissioned Mess--Open 740-64 EM Mess--Open (E-1/E-9) 740-66 Petty Officer Mess--Open 740-70 Mess--Open (E-7/E-9)	3572	574,092	6.22×10^{-6}
4 Buildings, Vacant	Not Used	87	--	--
6 Cafeterias 47 Stores--Commissary, Exchanges	730-13 Issue Retail Clothings/Uniforms 730-30 Bakery 740-01 to-09 Exchanges--Bldgs 740-20 Exchange--Temporary Housing 740-25 to-34 Exchanges, etc.--Bldgs 740-71 Exchanges--Package Stores	141	88,578	1.59×10^{-6}

*Titles for "Fire Codes" from References 2-6 and 2-8: titles for "Category Codes" from Reference 2-10.
**Σ1969 to 1975, area in 1000's of square feet.
#Fire Frequency units are number of fires per year per square foot.

Table 2-4. **Fire Frequency by Category Code (Continued)**

COMBINED FIRE FREQUENCY CODES*	COMBINED CATEGORY CODES*	NO. OF FIRES**	TOTAL AREA**	FIRE # FREQUENCY--P_i
7 Child Care Centers and Nursery	730-45 to-60 Dependent Schools 740-74 Child Care Center--Bldgs	7	3,276	2.14×10^{-6}
8 Church--Chapels	740-10, 11 Chapels and Religious Education--Bldgs	25	12,422	2.01×10^{-6}
9 Clubs--CPO 10 Clubs--EM 11 Clubs--Officers	740-63, 69 Clubs	171	19,497	8.77×10^{-6}
12 Cold Storage and/or Refrigeration Plants	431-all Cold Storage--Warehouses	9	21,821	4.12×10^{-7}
13 Communications	131-all Communications Bldgs 133-all Navigation and Traffic Aids--Bldgs	123	34,380	3.58×10^{-6}
14 Dispensaries and Dental Clinics	530-all Laboratories and Clinics Bldgs 540-all Dental Clinics--Bldgs 550-all Dispensaries--Bldgs	89	17,982	4.95×10^{-6}
15 Drydocks (not incorp.into methodology because not a bdlg)	213-10 Maintenance--Ships/Spares--Drydocks	18	33,619	5.35×10^{-7}
16 Dwellings--Duplex 17 Dwellings--Multifamily 18 Dwellings--Single-Family 19 Dwellings--Trailers	711-all Family Housing--Dwellings 712-all Family Housing--Trailers 740-21 Visitor Reception 740-22 Transient Housing	2273	775,667	2.93×10^{-6}

Table 2-4. Fire Frequency By Category Code (Continued)

COMBINED FIRE FREQUENCY CODE*	COMBINED CATEGORY CODE*	NO. OF FIRES**	TOTAL AREA**	FIRE # FREQUENCY--P_i
20 Electronic Data Processing 33 Offices, Administration, etc.	141-all Land Operational--Bldgs 142-10, 19 Land Operational--Helium Facilities 155-11 Small Craft Berthing-Fleet Landing Bldg 159-20, 30,64 Waterfront Operational--Other Bldgs 610-all Administrative--Offices, Data Processing Bldgs 620-all Administrative--Offices, Data Processing--Underground 740-12 Red Cross, Navy Relief--Bldgs 740-37 Special Services Issue Office 746-76 to 89 Miscel. Admin. Facilities	476	348,816	1.36×10^{-6}
21 Engine Test Cells 24 Hangars	211-05 to-58 Maintenance--Aircraft/Spares--Bldgs 211-60 to 62 211-70 to 77 211-85 to 86	113	233,307	4.84×10^{-7}
22 Flammable Liquids/Gases--Handling and/or Storage	Not Used	30	--	--
23 Garage (Dwelling)	714-all Family Housing--Detached Facilities--Bldgs 723-40 Bachelor Housing--Detached Facilities--Garage 723-60, 77 Troop Housing--Other Detached Bldgs	43	22,024	1.95×10^{-6}
25 Hospitals--Other than Wards, Surgery 26 Hospitals--Wards	510-all Hospitals--Bldgs	251	61,268	4.10×10^{-6}

Table 2-4. Fire Frequency by Category Code (Continued)

COMBINED FIRE FREQUENCY CODE*	COMBINED CATEGORY CODE*	NO. OF FIRES**	TOTAL AREA**	FIRE # FREQUENCY--P_f
27 Known, But Not Classified	730-10 Fire Stations 730-12 Hose Drying Facility 730-20 Police Stations 740-18 Bank 740-19 Credit Union 760-10 Museum and Memorials--Bldgs 730-65 Fallout Shelter 730-80 to 81 Misc. Bldgs	494	15,552	3.18×10^{-5}
28 Laboratories, Other than Medical	310-all Research, Development, Testing and Evaluation--Bldgs	126	133,752	9.42×10^{-7}
29 Laundries and/or Dry Cleaning	723-30 Bachelor Housing--Detached Facilities--Laundry 730-40 Laundry/Dry Cleaning Plant 740-13 Exchange, Laundry 740-15 Exchange, Dry Cleaning Plant	42	3,655	1.15×10^{-5}
31 Manufacturing, Processing, Industrial	223-10 Production--Ships/Spares--Bldgs 224-all Production--Tank/Automotive--Bldgs 225-all Production--Weapons/Spares--Bldgs 227-all Production--Electronics/Communications Equip.--Bldgs 228-all Production--Misc. Material and Equip.--Bldgs 229-40 to 80 Production--Construction and Misc. Materials--Bldgs	45	17,984	2.50×10^{-6}

Table 2-4. Fire Frequency by Category Code (Continued)

COMBINED FIRE FREQUENCY CODE*	COMBINED CATEGORY CODE*	NO. OF FIRES**	TOTAL AREA**	FIRE # FREQUENCY--P_f
32 Misc. Small Outlying Structures	125-20 Misc. Pipeline Facilities--Shelter 161-30 Harbor Protection Facilities--Winch House 179-40 Small Arms Range 730-66 to 70 Misc. Structures 723-20 Latrine, Detached 730-25 Gate/Sentry House 730-76 Kennel 730-75 Public Toilet 823-15 Gas Meter Shed 827-10 Transmission Line Shed 843-50 Fire Protect Value Shed 872-20 Guard and Watch Towers	102	3,007	3.39×10^{-5}
34 Magazine, Ordinance and/or Chemical Storage 35 Ordinance Manufacturing, Assembly, and Modification	212-all Maintenance--Guide Missiles--Bldgs 216-all Maintenance--Ammo/Explosives/Toxics--Shops 226-all Production--Ammo/Explosives/Toxics--Bldgs	330	296,557	1.11×10^{-6}
36 Outside Storage	Not Used	38	--	--
37 Piers, Wharves (not incorp. into methodology because not a bldg)	151-all Waterfront Operational--Piers 152-all Waterfront Operational--Wharves	90	235,269	3.82×10^{-7}
38 Power, Heat, Utilities	811-09 and 59 Electric Energy--Bldgs and Util 812-09 Electric Distribution--Bldgs and Shelter 813-10 Switching/Substation--Bldgs and Shelter 821-09 Heating Plant--Bldgs 822-09 Steam/Heat--Bldgs and Shelter 823-09 Gas Generating--Bldgs 826-10 Refrigeration/Air Conditioning Plants--Bldgs 730-78 Dairy Plant	201	52,116	3.86×10^{-6}

Table 2-4. Fire Frequency by Category Code (Continued)

COMBINED FIRE FREQUENCY CODE**	COMBINED CATEGORY CODE*	NO OF FIRES**	TOTAL AREA**	FIRE # FREQUENCY--P_i
38 Continued	831-09, 14,39 Sewage and Industrial Waste Treatment & Disposal--Bldgs 832-29 Sewage and Industrial Waste Collection--Pumping Stations 833-09 20,40 Solid Waste Handling Facilities --Bldgs 841-09 Water Treatment Facilities--Bldgs 842-09 Water Distribution--Potable--Bldgs 844-10 Water Supply and Storage--Non-potable--Bldgs 845-10 Water Distribution--Nonpotable --Bldgs 890-09, 45,77 Misc. Utilities Plants, Sheds, Shelter, Misc.	201	52,116	3.86×10^{-6}
40 Recreation--Gym, etc. 48 Theaters	730-35, 36 Locker Rooms 740-40 to 56 Recreation and Entertainment--Bldgs 740-75 Aero Club Facility	174	66,934	2.60×10^{-6}
41 Schools--Training	171-all Training--Bldgs	167	232,830	7.17×10^{-7}
42 Shipbuilding Ways	Not Used	5	--	--
43 Shops--Hobby	740-35 Hobby Shop--Amateur Radio 740-36 Hobby Shop--Arts/Crafts 740-38 Hobby Shop--Automotive 740-39 Entertainment Workshop Ctr	13	13,707	9.48×10^{-7}

Table 2-4. Fire Frequency by Category Code (Continued)

COMBINED FIRE FREQUENCY CODES*	COMBINED CATEGORY CODES*	NO OF FIRES**	TOTAL AREA**	FIRE # FREQUENCY--P_1
44 Shops--Misc. 45 Shops--O&R	213-41 to 77 Maintenance--Ships/Spares--Shops 214-10 to 53 Maintenance--Tank/Automotive--Shops 215-all Maintenance--Weapons/Spares--Shops 217-10 30,77 Maintenance--Weapons/Spares--Shops 218-all Maintenance--Misc. Material and Equip.--Bldgs 740-16 Exchange Maintenance Shop 740-17 Exchange Central Support Facility	156	250,821	6.22×10^{-7}
46 Shops--Public Works	219-10 to 30, 77 Maintenance--Public Works Repair and Operations--Bldgs	67	82,197	8.15×10^{-7}
49 Vehicles and Mobile Equipment	Not Used	771	--	--
50 Warehouses, Storehouses--Supply	153-20 Cargo Handling Facility--Waterfront Transit Shed 153-30 Cargo Handling Facility--Container Operations Bldg 155-21 Small Craft Boathouse 424-10 Weapon Related Battery Storage--Bldgs 441-10 to 35 70to73 General Supply--Storage Dep/Instln--Warehouse 730-77 Personnel Support Storage-Misc. 740-23 Commissary Inc Backup Storage 740-24 Commissary Cold Storage, Det	253	485,158	5.21×10^{-7}
	TOTAL	10,613		

A finer breakdown is required for some categories, particularly the 730 and 740 categories which encompass a plethora of different occupancies. To provide this finer breakdown, the aggregated category areas for prior years was apportioned according to the percentages existing on June 30, 1975. These percentages were calculated using the areas given in the Inventory of Military Real Property[2-11].

The first digit of the Category Code identifies the nine broad DOD facility classes:

Operational and Training Facilities	100 Series
Maintenance and Production Facilities	200 Series
Research, Development, and Test Facilities	300 Series
Supply Facilities	400 Series
Hospital/Medical Facilities	500 Series
Administrative Facilities	600 Series
Housing and Community Facilities	700 Series
Utilities and Ground Improvement	800 Series
Real Estate	900 Series

2.4 Damage Algorithms

The expected loss from fire is a function of many variables. Such things as the following may all affect the loss.

- the capability and quantity of the available fire fighting forces,
- the degree of engineered fire protection in the building,
- the type of construction,
- the type and quantity of the building's contents (i.e., the fire load), and
- the quality of the building's construction and workmanship.

Very few of these parameters can be specified deterministically, even for a specific building. As a result, this randomness forces one to develop a probabilistic model for expected fire damage. Although Lie [2-3,2-4] and Burros [2-2] have developed such models for the failure of a building from fire, their models are not presently applicable to our situation. The reason they are unuseable is that they require knowledge of certain parameters, particularly the building's fire resistance, which is unknown to us.

With this restriction in mind, an alternative approach must be devised. The classical approach would be to use a statistical (i.e., frequentist) approach. This, however, would require extensive data on the frequency of different amounts (i.e., percentages) of damage which also are not available. Several authors have discussed the problem of developing classical probabilistic models when adequate statistical data is not available. Although much of this work has been done in other areas, such as marine spills[2-12] and earthquakes[2-13],

their conclusions also seem to be applicable to the question of fire damage:

> The probabilistic approach is the only theoretically sound basis to use, even though sufficient data to develop it through the classical approach does not exist.

For problems where there is sufficient data, it is possible to develop a probabilistic model using a classical statistical approach. This was, in fact, the approach used in developing the fire frequency model. However, lack of data on the amount (i.e., percentage of value lost) of damage incurred from fire, precludes the use of the statistical approach for this aspect of the fire model. Under this restriction it is necessary to approach the probabilistis problem from a Bayesian viewpoint. The Bayesian approach considers, in addition to the data, the subjective opinions of knowledgeable people in determining probabilities [2-12].

The method of analysis used here to develop a fire damage algorithm can be considered in the following four steps:

- Formulate the probabilistic damage model.
- Establish the significant parameters and determine those which can be handled explicitly.
- Quantify the probabilistic model using the subjective probabilities.
- Analyze the results.

The present probabilistic damage model utilizes the concept of a Damage Probability Matrix (DPM), a concept previously used by Whitman, et al., for earthquake[2-13]. Figure 2-2 shows the DPM's that were developed. The level of damage is described by a series of damage states. Each number in the matrix describes the probability that a particular state of damage will occur, given that a loss (loss > $1.00) fire is experienced. The DPM is simply a means of organizing our opinions concerning the variability of damage. The numbers in each column must sum to unity.

The significant parameters which can be handled explicitly are:

- The level of fire protection
  - 1 - no fire protection
  - 2 - automatic fire suppression devices
  - 3 - automatic fire detection systems
  - 4 - both automatic suppression and detection systems
- Type of construction
  - 1 - fire resistive
  - 2 - non-combustible
  - 3 - ordinary or wood frame
- Type of interior finish
  - 1 - non-combustible
  - 2 - combustible
- Fire load
  - 1 - light
  - 2 - moderate
  - 3 - severe

Figure 2-2a. Damage Matrix One - Buildings with No Fire Protection Other than That Inherent in Their Construction

DAMAGE STATE	CONSTRUCTION TYPE / INTERIOR FINISH / FIRE LOAD / DAMAGE RANGE	FIRE RESISTIVE						NON-COMBUSTIBLE						ORDINARY/WOOD FRAME					
		FIRE RESISTIVE			COMBUSTIBLE			FIRE RESISTIVE			COMBUSTIBLE			FIRE RESISTIVE			COMBUSTIBLE		
		LIGHT	MODERATE	SEVERE	LIGHT	MODERATE	SEVERE	LIGHT	MODERATE	SEVERE	LIGHT	MODERATE	SEVERE	LIGHT	MODERATE	SEVERE	LIGHT	MODERATE	SEVERE
MINOR	0 TO 10% DAMAGE TO ONE FIRE AREA	0.72	0.65	0.52	0.58	0.52	0.46	0.70	0.61	0.48	0.53	0.42	0.36	0.52	0.41	0.31	0.31	0.23	0.20
LIGHT	10 TO 50% DAMAGE TO ONE FIRE AREA	0.16	0.16	0.17	0.23	0.25	0.19	0.16	0.20	0.17	0.18	0.20	0.17	0.18	0.23	0.18	0.20	0.16	0.14
MODERATE	50 TO 100% DAMAGE TO ONE FIRE AREA	0.08	0.13	0.19	0.12	0.15	0.20	0.09	0.11	0.15	0.13	0.19	0.25	0.14	0.17	0.19	0.19	0.27	0.24
HEAVY	ADJACENT FIRE AREAS HAVING UP TO 50% DAMAGE	0.03	0.04	0.07	0.05	0.05	0.08	0.03	0.04	0.09	0.08	0.09	0.10	0.10	0.11	0.18	0.14	0.16	0.18
TOTAL	BUILDING TOTALLY DESTROYED	0.01	0.02	0.05	0.02	0.03	0.07	0.02	0.04	0.11	0.08	0.10	0.12	0.06	0.08	0.14	0.16	0.18	0.24

CONSTRUCTION TYPE (IN ORDER OF DECREASING FIRE RESISTANCE)

- FIRE RESISTIVE - PRINCIPAL SUPPORTING MEMBERS HAVE 3 OR 4 HOURS FIRE RATING; SECONDARY STRUCTURAL MEMBERS HAVE 2 OR 3 HOURS FIRE RATING.
- NON-COMBUSTIBLE - CONSTRUCTED OF MATERIALS WHICH DO NOT CONTRIBUTE FUEL TO FIRE. IF "PROTECTED", HAS FIRE-RESISTIVE WALLS, FLOORS, AND ROOF.
- ORDINARY - EXTERIOR WALLS HAVE NON-COMBUSTIBLE MATERIALS PROVIDING SOME PROTECTION TO OTHER BUILDINGS.
- WOOD FRAME - ORDINARY WOOD FRAME CONSTRUCTION PROVIDING NO PROTECTION TO OTHER BUILDINGS.

INTERIOR FINISH

- FIRE RESISTIVE - THE INTERIOR FINISH IS PRIMARILY COMPOSED OF MATERIALS WHICH WOULD NOT BE EXPECTED TO BURN. INCLUDED HERE WOULD BE GYPSUM BOARD, PLASTER, CONCRETE, MASONRY, METAL, NON-WOOD-BASED ACOUSTICAL TILE, GLASS BLOCK.
- COMBUSTIBLE - THE INTERIOR FINISH IS PRIMARILY COMPOSED OF MATERIALS WHICH CONTRIBUTE SIGNIFICANT AMOUNTS OF FUEL. INCLUDED HERE WOULD BE WOOD-BASED MATERIALS, FIBERBOARD, PLASTIC PANELS, CARPETING, RESILIENT FLOORING (VINYL, RUBBER, LINOLEUM, ETC.), DRAPES.

FIRE AREA

- A FIRE AREA IS AN AREA OF A BUILDING FLOOR SEPARATED FROM THE REST OF THE BUILDING BY SOME TYPE OF BARRIER WHICH WILL SLOW DOWN OR PREVENT THE SPREAD OF FIRE AND SMOKE.

FIRE LOAD

- L = LIGHT - SMALL QUANTITES OF COMBUSTIBLES SUCH AS METAL-GOODS WAREHOUSES OR METALWORKING WITH NO CUTTING OILS, HOSPITALS, OFFICES, AUDITORIUMS, SCHOOLS, THEATERS, BARRACKS, AND DWELLINGS.
- M = MODERATE - MANUFACTURE AND/OR PROCESSING OF TEXTILES, HARDWARE, AND FOOD; METALWORKING USING CUTTING OILS; OTHER OCCUPANCIES NOT CLASSIFIED AS LIGHT OR SEVERE HAZARD, OFFICES, INSTITUTIONS, STORES, AND GARAGES.
- S = SEVERE - CONCENTRATION OF COMBUSTIBLE STORAGE SUCH AS LUMBER; FURNITURE; TEXTILE; PAPER OR RUBBER PRODUCTS; CRATED HARDWARE, PARTICULARLY WHEN IN HIGH PILES OR TIERED RACKS; CONGESTED MERCANTILE OCCUPANCIES; PROCESSING OR STORAGE OF FLAMMABLE LIQUIDS OR HAZARDOUS CHEMICALS.

DAMAGE STATE

- MINOR - ONLY ONE FIRE AREA INVLOVED. LESS THAN 10 PERCENT OF THE VALUE OF THE FIRE AREA'S STRUCTURE AND CONTENTS ARE LOST FROM FIRE, SMOKE, OR WATER DAMAGE.
- LIGHT - ONLY ONE FIRE AREA INVOLVED. BETWEEN 10 TO 50 PERCENT OF THE VALUE OF THE AREA'S STRUCTURE AND CONTENTS ARE LOST FROM FIRE, SMOKE, OR WATER DAMAGE.
- MODERATE - ONLY ONE FIRE AREA INVLOVED. BETWEEN 50 AND 100 PERCENT OF THE VALUE OF THE AREA'S STRUCTURE AND CONTENTS ARE LOST FROM FIRE, SMOKE, OR WATER DAMAGE.
- HEAVY - THE INITIAL FIRE AREA IS COMPLETELY DESTROYED. ADJACENT FIRE AREAS SUFFER UP TO 50 PERCENT DAMAGE.
- TOTAL - THE ENTIRE BUILDING AND ITS CONTENTS ARE DESTROYED.

Figure 2-2b. Damage Matrix Two - Buildings with Automatic Fire Detection Systems

DAMAGE STATE	CONSTRUCTION TYPE / INTERIOR FINISH / FIRE LOAD / DAMAGE RANGE	FIRE RESISTIVE						NON-COMBUSTIBLE						ORDINARY/WOOD FRAME					
	INTERIOR FINISH	FIRE RESISTIVE			COMBUSTIBLE			FIRE RESISTIVE			COMBUSTIBLE			FIRE RESISTIVE			COMBUSTIBLE		
	FIRE LOAD	LIGHT	MODERATE	SEVERE	LIGHT	MODERATE	SEVERE	LIGHT	MODERATE	SEVERE	LIGHT	MODERATE	SEVERE	LIGHT	MODERATE	SEVERE	LIGHT	MODERATE	SEVERE
MINOR	0 TO 10% DAMAGE TO ONE FIRE AREA	0.80	0.69	0.60	0.65	0.59	0.54	0.70	0.67	0.52	0.55	0.50	0.46	0.58	0.54	0.43	0.46	0.40	0.33
LIGHT	10 TO 50% DAMAGE TO ONE FIRE AREA	0.15	0.19	0.14	0.20	0.17	0.19	0.19	0.18	0.16	0.22	0.23	0.17	0.20	0.20	0.18	0.23	0.23	0.19
MODERATE	50 TO 100% DAMAGE TO ONE FIRE AREA	0.04	0.08	0.20	0.10	0.15	0.13	0.07	0.10	0.15	0.11	0.13	0.15	0.10	0.12	0.15	0.12	0.14	0.15
HEAVY	ADJACENT FIRE AREAS HAVING UP TO 50% DAMAGE	0.01	0.03	0.04	0.03	0.07	0.08	0.03	0.03	0.09	0.05	0.06	0.12	0.08	0.09	0.14	0.09	0.11	0.18
TOTAL	BUILDING TOTALLY DESTROYED	0.00	0.01	0.02	0.02	0.02	0.06	0.01	0.02	0.08	0.07	0.08	0.10	0.04	0.05	0.10	0.10	0.12	0.15

Figure 2-2c. Damage Matrix Three - Buildings with Automatic Sprinkler Systems or Other Automatic Fire Suppression Devices

DAMAGE STATE	CONSTRUCTION TYPE / INTERIOR FINISH / FIRE LOAD / DAMAGE RANGE	FIRE RESISTIVE						NON-COMBUSTIBLE						ORDINARY/WOOD FRAME					
	INTERIOR FINISH	FIRE RESISTIVE			COMBUSTIBLE			FIRE RESISTIVE			COMBUSTIBLE			FIRE RESISTIVE			COMBUSTIBLE		
	FIRE LOAD	LIGHT	MODERATE	SEVERE	LIGHT	MODERATE	SEVERE	LIGHT	MODERATE	SEVERE	LIGHT	MODERATE	SEVERE	LIGHT	MODERATE	SEVERE	LIGHT	MODERATE	SEVERE
MINOR	0 TO 10% DAMAGE TO ONE FIRE AREA	0.90	0.85	0.82	0.81	0.80	0.78	0.87	0.85	0.80	0.79	0.78	0.76	0.77	0.75	0.71	0.72	0.67	0.63
LIGHT	10 TO 50% DAMAGE TO ONE FIRE AREA	0.07	0.10	0.07	0.11	0.09	0.11	0.09	0.10	0.09	0.13	0.15	0.09	0.12	0.10	0.13	0.10	0.11	0.12
MODERATE	50 TO 100% DAMAGE TO ONE FIRE AREA	0.02	0.04	0.09	0.06	0.06	0.06	0.02	0.03	0.05	0.05	0.04	0.05	0.08	0.09	0.09	0.09	0.08	0.09
HEAVY	ADJACENT FIRE AREAS HAVING UP TO 50% DAMAGE	0.01	0.01	0.01	0.01	0.04	0.04	0.01	0.01	0.05	0.02	0.02	0.08	0.02	0.05	0.05	0.07	0.08	0.06
TOTAL	BUILDING TOTALLY DESTROYED	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.01	0.02	0.02	0.06	0.10

Figure 2-2d. Damage Matrix Four - Buildings with Both an Automatic Fire Suppression System and an Automatic Fire Detection System

DAMAGE STATE	CONSTRUCTION TYPE / INTERIOR FINISH / FIRE LOAD / DAMAGE RANGE	FIRE RESISTIVE						NON-COMBUSTIBLE						ORDINARY/WOOD FRAME					
		FIRE RESISTIVE			COMBUSTIBLE			FIRE RESISTIVE			COMBUSTIBLE			FIRE RESISTIVE			COMBUSTIBLE		
		LIGHT	MODERATE	SEVERE	LIGHT	MODERATE	SEVERE	LIGHT	MODERATE	SEVERE	LIGHT	MODERATE	SEVERE	LIGHT	MODERATE	SEVERE	LIGHT	MODERATE	SEVERE
MINOR	0 TO 10% DAMAGE TO ONE FIRE AREA	.99	.97	.94	.95	.94	.93	.97	.97	.95	.91	.91	.90	.94	.93	.89	.89	.82	.78
LIGHT	10 TO 50% DAMAGE TO ONE FIRE AREA	.01	.03	.02	.04	.04	.04	.03	.03	.03	.06	.07	.05	.04	.05	.06	.05	.09	.07
MODERATE	50 TO 100% DAMAGE TO ONE FIRE AREA	0	0	.04	.01	.02	.03	0	0	.02	.03	.02	.03	.02	.02	.03	.03	.03	.04
HEAVY	ADJACENT FIRE AREAS HAVING UP TO 50% DAMAGE	0	0	0	0	0	0	0	0	0	0	0	.02	0	0	.02	.03	.03	.04
TOTAL	BUILDING TOTALLY DESTROYED	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	.03	.07

Figure 2-2d was developed in house using data from Figures 2-2b and 2-2c.

70

Figure 2-2e. Standard Deviations

CONSTRUCTION TYPE	FIRE RESISTIVE						NON-COMBUSTIBLE						ORDINARY/WOOD FRAME					
INTERIOR FINISH	FIRE RESISTIVE			COMBUSTIBLE			FIRE RESISTIVE			COMBUSTIBLE			FIRE RESISTIVE			COMBUSTIBLE		
DAMAGE STATE \ FIRE LOAD	LIGHT	MODERATE	SEVERE	LIGHT	MODERATE	SEVERE	LIGHT	MODERATE	SEVERE	LIGHT	MODERATE	SEVERE	LIGHT	MODERATE	SEVERE	LIGHT	MODERATE	SEVERE
BUILDINGS WITH NO FIRE PROTECTION OTHER THAN THAT INHERENT IN THEIR CONSTRUCTION																		
MINOR	0.17	0.21	0.26	0.23	0.25	0.25	0.17	0.19	0.23	0.23	0.24	0.23	0.26	0.25	0.20	0.20	0.20	0.18
LIGHT	0.13	0.10	0.09	0.18	0.22	0.11	0.13	0.16	0.08	0.11	0.11	0.09	0.11	0.23	0.11	0.12	0.11	0.11
MODERATE	0.08	0.12	0.23	0.11	0.18	0.23	0.07	0.08	0.11	0.09	0.15	0.23	0.10	0.11	0.12	0.14	0.23	0.14
HEAVY	0.03	0.05	0.07	0.05	0.05	0.06	0.03	0.04	0.08	0.07	0.08	0.09	0.09	0.09	0.22	0.09	0.10	0.10
TOTAL	0.01	0.03	0.09	0.03	0.03	0.14	0.03	0.05	0.21	0.21	0.23	0.23	0.07	0.08	0.19	0.21	0.23	0.22
BUILDINGS WITH AUTOMATIC FIRE DETECTION SYSTEMS																		
MINOR	0.14	0.26	0.29	0.25	0.29	0.29	0.20	0.20	0.26	0.25	0.26	0.25	0.22	0.22	0.25	0.29	0.28	0.30
LIGHT	0.13	0.17	0.09	0.15	0.12	0.11	0.18	0.15	0.09	0.22	0.22	0.09	0.15	0.13	0.09	0.06	0.07	0.07
MODERATE	0.04	0.08	0.28	0.10	0.19	0.11	0.05	0.07	0.12	0.08	0.09	0.13	0.06	0.08	0.09	0.13	0.08	0.10
HEAVY	0.02	0.02	0.04	0.04	0.11	0.08	0.04	0.04	0.11	0.05	0.05	0.23	0.08	0.08	0.09	0.13	0.12	0.08
TOTAL	0.01	0.01	0.03	0.03	0.03	0.14	0.02	0.03	0.18	0.20	0.23	0.23	0.05	0.05	0.03	0.04	0.12	0.24
BUILDINGS WITH AUTOMATIC SPRINKLER SYSTEMS OR OTHER AUTOMATIC FIRE SUPPRESSION DEVICES																		
MINOR	0.15	0.26	0.26	0.27	0.26	0.25	0.21	0.18	0.25	0.27	0.26	0.25	0.27	0.26	0.25	0.29	0.28	0.30
LIGHT	0.11	0.17	0.08	0.14	0.10	0.11	0.17	0.14	0.10	0.24	0.24	0.08	0.13	0.08	0.09	0.06	0.07	0.07
MODERATE	0.03	0.08	0.24	0.13	0.12	0.08	0.04	0.04	0.06	0.07	0.06	0.06	0.13	0.12	0.09	0.13	0.08	0.10
HEAVY	0.02	0.02	0.03	0.02	0.12	0.08	0.02	0.02	0.12	0.03	0.03	0.24	0.04	0.12	0.09	0.13	0.12	0.08
TOTAL	0.00	0.01	0.01	0.01	0.01	0.02	0.01	0.02	0.02	0.02	0.02	0.03	0.02	0.02	0.03	0.04	0.12	0.24

Parameter one is handled by forming a separate DPM for each subdivision. The remaining three parameters are handled within each DPM as shown in Figure 2-2.

The determination and subdivision of the significant parameters was established from a review of the literature and from discussions with experienced individuals. Obviously, much judgment and compromising was required to condense all of the possible factors down to a number that was practical and yet comprehensive enough to reflect important differences. Consequently, such things as differences in water damage due to different types of sprinkler systems, building age, multiple types of occupancies in the same building, variability of detection systems, etc., have all had to be blended together. These variables are only reflected through the probability values themselves.

The DPM's were quantified with the use of a survey of naval fire damage experts.* The people participating in the survey included Fire Chiefs, Area Fire Marshals, and Fire Protection Engineers. Approximately 45 people were contacted, out of which 18 chose to participate. Each survey participant was asked to fill out three damage matrices of the type shown in Figure 2-2: one for unprotected buildings, one for buildings with automatic detection systems, and one for buildings with automatic fire suppression systems. This data was then processed according to the techniques described below. A summary of the results was then provided to each participant. The purpose of this feedback was to show each participant where his estimates fell relative to those of the rest of the group. Each participant then had the opportunity to refine his

*One survey participant was with another government agency.

estimates or correct responses which may have resulted from initial misinterpretation of the questionnaire. The flow chart shown in Figure 2-3 summarizes the survey operation.

The initial estimates exhibited quite a spread among the 15 responders, a spread which was reduced very little by the second iteration. Only two of the initial responders saw fit to update their first estimate on the second iteration, although three new responses were obtained.

The resulting eighteen samples in each category were averaged. The standard deviation for each DPM value is also included in Figure 2-2 (Part e).

The fire load is the amount of cellulose (8000 BTU per pound) measured in pounds per square foot (psf) that will generate the same amount of heat when totally burned as the actual contents of the building. The three categories used for these damage matrices correspond to categories used by Miller, et al [2-7].

Light - up to 15 psf combustible loading
Moderate - 15 to 40 psf combustible loading
Heavy - more than 40 psf combustible loading

The DPM's resulting from this survey and selected for use in this fire-hazard methodology are presented in Figures 2-2a, b, and c. An additional DPM was constructed in-house for the case when both sprinkler and automatic detection systems are installed (Figure 2-2d).

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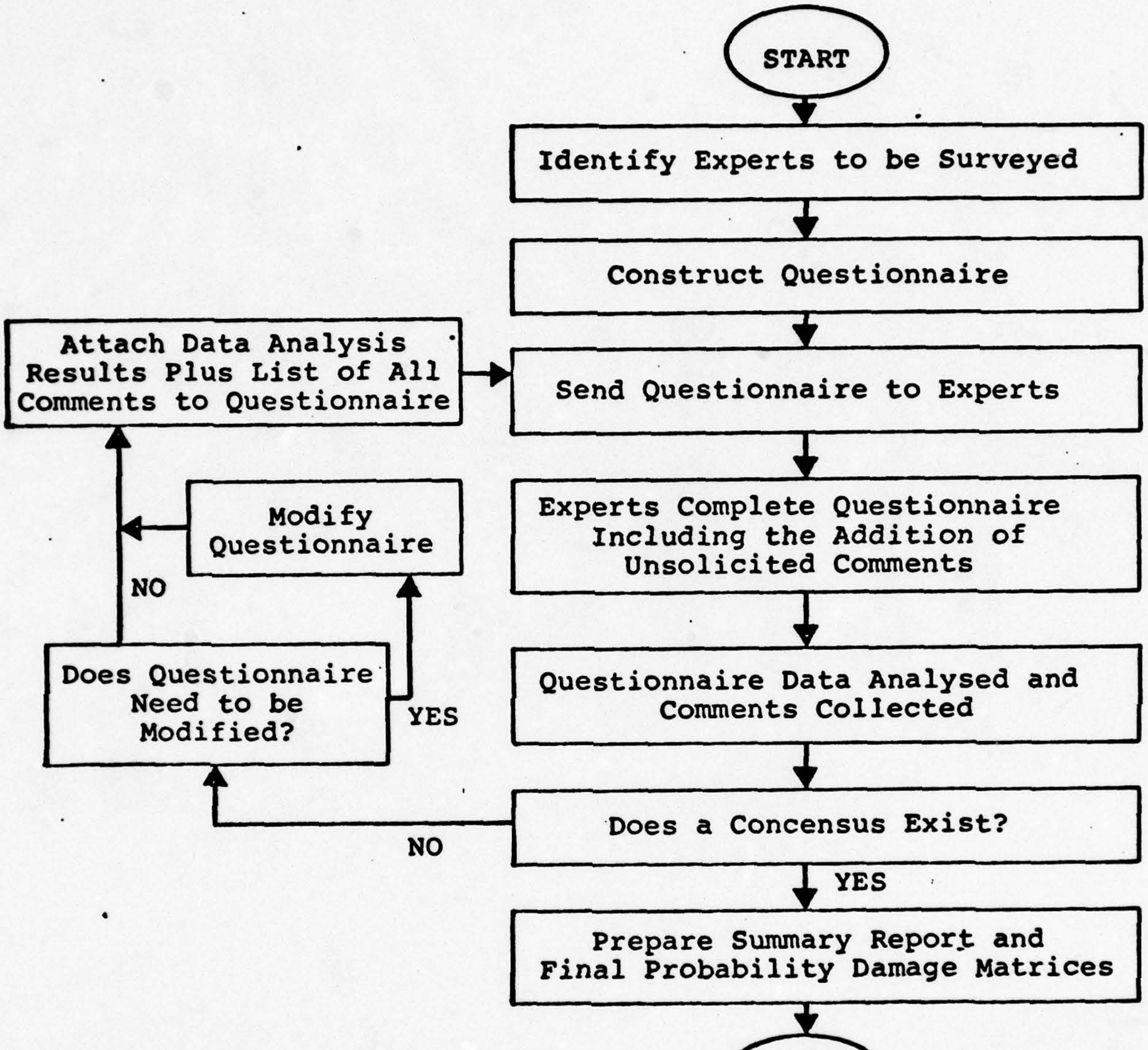

In practice only one iteration could be performed due to project constraints and lack of a significant number of responses to the second questionnaire.

Figure 2-3. Flow Chart of Expert Survey Procedures

2.5 Expected Losses

2.5.1 Economic Losses

Three kinds of information are needed to determine the expected economic loss:

- the probability of having a fire (i.e., the hazard model),
- the probability of having each of the five damage states if a fire occurs (i.e., the damage algorithm),
- the replacement cost of the structure and its contents (i.e., the exposure model).

The expected loss in t years is then determined using

$$E\langle LOSS\rangle = \sum_{j=1}^{5} V\, Q_j\, D_j \sum_{\nu=1}^{\infty} \nu\, P_f(\gamma)$$

$$= \sum_{j=1}^{5} V\, Q_j\, D_j\, (p_m t) \qquad (2\text{-}3)$$

where

j = damage state index

V = total value exposed (building and contents)

Q_j = probability that damage state j occurs given a fire occurs (Damage Algorithm)

D_j = ratio of repair cost to total replacement cost

= .05/N	j=1 (Minor Damage)
= .30/N	j=2 (Light Damage)
= .75/N	j=3 (Moderate Damage)
= 1.00	j=4 and N≤5 (Heavy Damage)
= 5.00/N	j=4 and N>5
= 1.00	j=5 (Total Damage)

ν = number of fires

$P_f(\nu)$ = probability that exactly γ fires will occur (Hazard Model, Equation [2-1])

N = number of fire areas

p_m = mean number of fires per year in the subject building

t = time in years

To get the expected average annual loss, set t = 1, and use the relation $p_m = p_i A$

$$E\langle LOSS\rangle = \sum_{j=1}^{5} V\, Q_j\, D_j\, p_i A \tag{2-4}$$

where

p_i = fire rate (number of fires/year/unit area)

A = total area of building

Note that for small buildings or those with just a few fire areas ($N \leq 5$), heavy and total damage both represent a total loss of the structure and its contents.

A number of important assumptions are implied in the above formulation. These assumptions cannot be fully substantiated at this time. However, these assumptions could be substantiated or the algorithm upgraded if 1) additional data on the building and its contents were obtained and 2) naval statistical fire data were upgraded to provide information on percent damage (see Section 2.7). Among the implied assumptions are

- All fire areas are of same size,
- Value of building and contents uniformly distributed throughout building,

- Damage percentage equal to average of upper and lower extreme
- Building has only one type of occupancy for purposes of choosing P_f, the fire probability.

2.5.2 Mission Losses

The problem of determining the mission reliability is discussed in Section 6.1. That methodology requires the reliability of each structure in the mission network which is developed below.

The probability of failure is defined as

$$P(\text{failure}) = P(D_j > 50\% \text{ to one fire area} \mid \text{a fire occurs})$$

$$P(\text{failure}) = \begin{cases} 1 & D_j > 50\%,\ \nu > 0 \\ 0 & D_j > 50\%,\ \nu = 0 \\ 0 & D_j < 50\%,\ \nu > 0 \\ 0 & D_j < 50\%,\ \nu = 0 \end{cases}$$

By unconditioning, we obtain

$$P(\text{failure}) = P(D_j > 50\% \mid \nu > 0) \cdot P(\nu > 0)$$

$$P(\text{failure}) = \sum_{j=3}^{5} Q_j (1-e^{-P_m t}) \tag{2-5}$$

Therefore, the reliability of a structure is defined by equation 2-6. t is set to 1 to obtain the reliability for a one year period.

$$\text{RELIABILITY} = 1 - P(\text{failure})$$

$$= 1 - \sum_{j=3}^{5} Q_j (1-e^{-P_m t})$$

$$= 1 - (1-e^{-P_i A}) \sum_{j=3}^{5} Q_j \tag{2-6}$$

Implicit in this formulation is the assumption that the building has become non-functional when it sustains more than 50 percent damage to one fire area. This is a rather arbitrary determination, but one that can very easily be changed should naval experience provide justification for a different value. This assumption is certainly not valid for high-rise buildings with many fire areas. Indeed fire experience has shown that high-rise buildings have contained most fires to their area of origin with only minor disruptions to the remainder of the building[2-16]. However, the number of high-rise buildings on naval facilities must be small if, indeed, any exist at all.

2.5.3 Personnel Losses

One of the objectives of the study was to provide a methodology which could be used to minimize the risk of loss of life or personal injury while providing equal levels of protection from the four hazards. An investigation into the state of the art of fire protection and the availability of fire statistics, however, has shown that, at the present time, this is not possible.

Although extensive (but often conjectural) data exists on the number of fire casualties in the United States, there is no way to develop a casualty rate in terms of the number of people in the building when a fire starts. In addition, most fire deaths are single fatalities resulting from poor personal habits or bad judgement on the part of the victim. Provided that the basic, well-established, fire-protection principles are followed (as naval regulations require), any additional mitigations available to NAVFAC will have little effect on the number of deaths and injuries.

A review of naval fire data for the last seven years[2-8] yields the following information:

Total Deaths, Naval On-Shore Facilities (1969--1975)	49
Due to heart attacks, bad judgement, careless smoking, negligence	12
Vehicle explosions including an aircraft crashing into a hangar	26
Others (where damage and construction of building may have had some influence)	11

Of the 49 deaths over the seven-year period, only eleven were found to be in any way related to the design and construction of a building. Even if data existed, which it doesn't, to create a death rate based on the number of people present, the number of deaths would be statistically insignificant.

There was a total of 768 direct and 565 indirect injuries from fire over the same period. Although these values cannot be broken down to determine how many were related to the design and construction of buildings, there is no reason to assume the conclusion would be any different.

Not only is the naval fire experience statistically insignificant for the generation of a casualty rate, but both it and the national data do not provide the necessary data on the number of people exposed to fire.

Furthermore, the fatality rate (fatalities per person-hour) is already equal to the universal level of acceptable risk for involuntary hazards of about 10^{-9} fatalities per person-hour of exposure (see Section 1.2). For the period reviewed (1969 to 1975) Navy and Marine Corps had roughly 890,000 active duty personnel[2-18]; 330,000 civilian personnel[2-17], and 250,000

dependents [estimated] living on naval bases. If each of the military and civilian personnel spent 1600 hours (200 working days) at the facilities and the dependents 6720 hours (280 days), a fatality rate of only 2×10^{-9} would result including <u>all</u> fire fatalities. Moreover, on using just the fatalities which may have been influenced by the design and construction of the building, this rate reduces to 4×10^{-10}.

Of particular concern is the risk to people in high-rise structures because of the inability to evacuate these buildings in a timely fashion. Even here, however, the data base is inadequate. Fire fatalities occurring in high-rise buildings within the United States are "statistically insignificant" [2-16] even though the threat of a disaster exists and is of increasing concern. Loss of life from fires in high-rise buildings was a rare event during a thirty-year period ending in 1960, probably because so few of these buildings existed. The recent well-publicized fires in Korea, Brazil, and Alabama involved the violation of well-established traditional fire protection principles. Consequently, they are not even applicable to naval facilities.

Smoke detectors and alarm systems are basically a death and injury mitigation (except when they are directly linked to a manned fire station). It may be that the current use of these devices together with non-physical measures is responsible for the present death and injury rate being so low at naval shore facilities. Certainly the installation of automatic detection and alarm system would serve to eliminate those deaths preventable by physical measures.

For the above reasons, it was found to be both unnecessary and infeasible to develop a mitigation methodology applicable to death and injury from fire.

2.6 Methodology

The methodology for fire requires the initial input of certain data. This data comprises six types: hazard and damage, exposure and vulnerability, and mitigation and cost. A list of this data with corresponding sources was discussed in detail in Section 2-1.

To begin the analysis, the structure's identification number, major occupancy, current level of fire protection, and floor and surface area must be provided. These are shown in Figure 2-4 as in-line input data. Additional data, shown being received from the side, is that used for all structures. These data include the fire probabilities, damage matrices, and cost factors. These cost factors represent those utilized in assessing the cost for existing structures. The next step is to determine the current level of fire protection. There are four separate levels: no protection, protection by detection system, protection by sprinkler system, and protection by both detection and sprinkler systems. Existing structures have been inspected, as described in Section 7, to obtain this information. Once this is determined by the methodology, the appropriate branch can be followed. In viewing the flow chart on Figure 2-4, note that a specific structure will follow only one branch depending on its present level of fire protection.

Once the level of protection has been established, the next step involves classifying the interior finish. Here, two categories exist: non-combustible and combustible. If the structure has combustible interior finish, fireproofing is considered as well as all those mitigations mentioned earlier. Only mitigations not already present are considered.

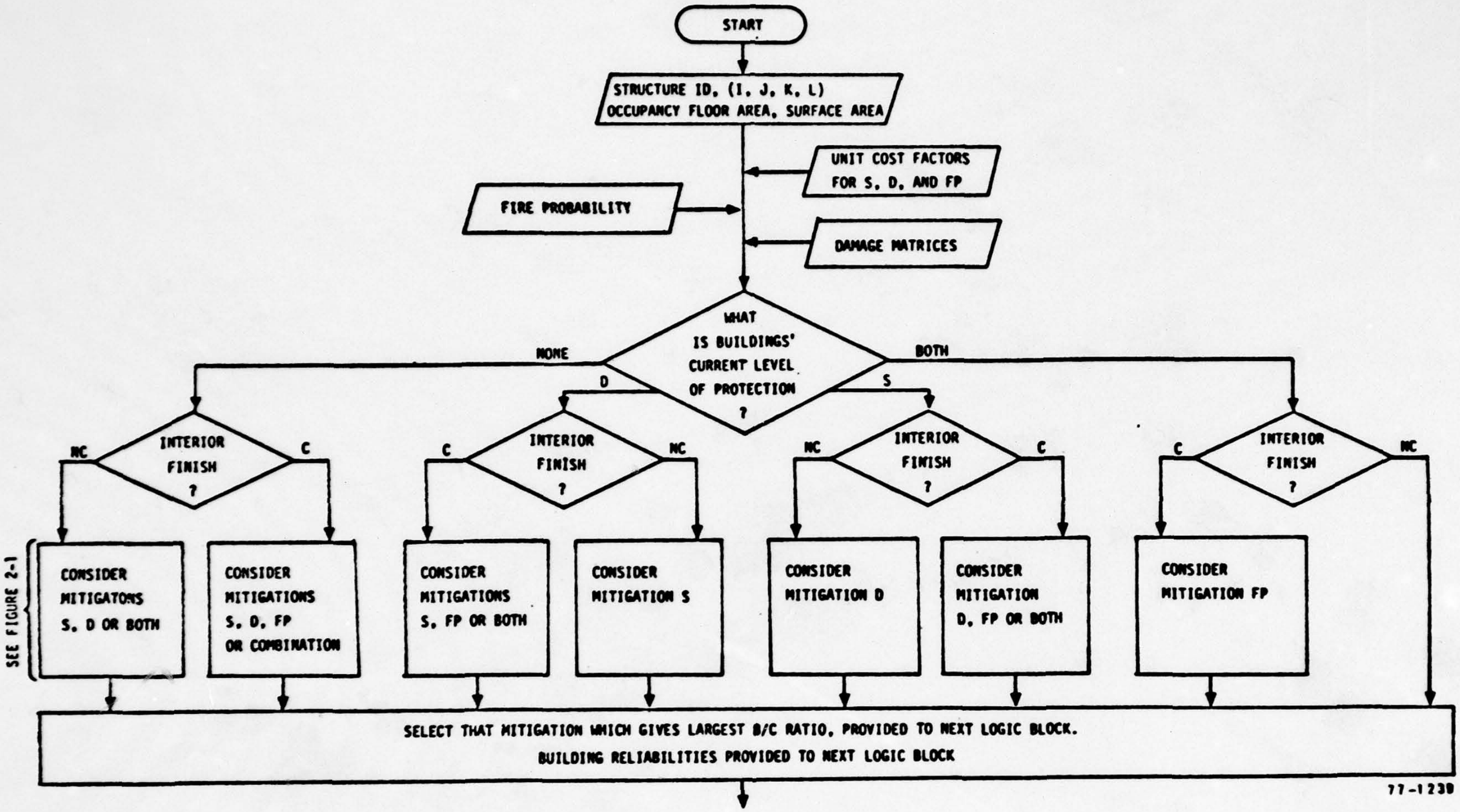

Figure 2-4. Fire Hazard

The selection of the best mitigation or combination of mitigations comes out of the benefit/cost analysis. Each mitigation, when implemented, produces a reduction in expected damage. This reduction is obtained by utilizing the information given in the fire damage matrices together with the expected damage equation (Equation 2-3). The various possible mitigations, or combination of mitigations that are considered in this methodology are:

- automatic sprinkler system*
- automatic detection system
- fireproofing
- automatic sprinkler system* and fireproofing
- detection system and fireproofing
- detection and sprinkler systems
- detection system, sprinkler system, and fireproofing

For example, if the structure has no fire protection and a non-combustible interior finish, the following mitigations are considered:

- automatic detector system
- automatic sprinkler system
- automatic detection and sprinkler systems

Similar lists exist for all combinations of levels of protection and interior finish.

---

*Light and ordinary occupancies - 1 head/112.5 ft^2 [2-19]
Extra hazardous occupancies - 1 head/72.0 ft^2

In addition to the reduction in expected damage, there exists a cost for implementing the mitigation. These two inputs represent the benefit and cost, respectively. Using this information, benefit/cost ratios are calculated for each set of mitigations.* The largest ratio is selected and the corresponding mitigation is sent to the next logic block (Figure 1-3). The basic methodology is the same for all branches.

2.7 Availability and Adequacy of Data

Naval data necessary to generate the fire frequency parameter, p_i, for specific building occupancies does exist but not in a usable form. This was previously pointed out by Miller, Krasner, and Wiener[2-7] in 1971 and the situation has not changed appreciably since then. The quantity of data has increased however, just due to the invervening four years. This improvement is, however, partially suppressed by the fact that real property inventories prior to 1961 are not now available.

The previous authors used industrial data where needed instead of naval data. This was adequate at that time because they were interested primarily in a relative ranking rather than an absolute ranking. However, in order to compare different hazards, an absolute ranking is required. This necessitates the use of the existing naval data in its present format.

*The effect of a discount rate need not be considered here because only one building is under consideration. The discount rate only enters into the picture when comparing different buildings (see Section 6).

The basic problem is that the occupancy categories used in the fire loss reports[2-6] cannot always be related to corresponding property categories used in the real property inventories[2-9]. This results in the consolidation of different property category codes involving widely diverse occupancies, less precise fire frequencies, and less confidence in the final result. If existing data were properly formatted and if additional data were accumulated to be fed into the system, the risk mitigation methodology would improve. However, the sensitivity of the methodology to these improvements cannot be stated at this time.

Another source of inexactness in the fire hazard model involves the real property inventory data. Here, continual changes in the category code, nomenclature, and units of measure make it difficult to aggregate the total building areas over a broad time span. Although the current version of NAVFAC P-72[2-10] accurately defines the present breakdown, many questions and inconsistencies arise when trying to use the inventory data for prior years. Premature disposal of earlier inventory may also be limiting the size of the data base available for analysis. Although the fire occurrence data has existed in its present form for many years, much of it is not usable because of the lack of corresponding inventory data. The fire occurrence and loss statistics must be interpreted with full recognition of the changing size, value, and nature of the shore establishment. And this can only be done if accurate inventory data is also available for the same period. The accuracy of the inventory data was not investigated, but any significant errors would obviously affect the fire frequency parameter. (See Table 2-3 footnotes for examples of the problems encountered.)

2.8 Reference for Fire

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3. WIND HAZARD

3.1 Introduction

The methodology developed for the evaluation of the wind hazard mitigations is discussed in this section. The salient features of the approach are summarized in Table 3-1. The procedure to be used to determine the risk from the wind hazard is introduced in Figure 3-1. The meaning of each block will be explained in the following sections. The hazard model presented here was developed jointly for this study and a concurrent study performed for the National Science Foundation [3-20].

The wind hazard was divided into three categories (tornado, severe wind, and hurricane) because of the widely different natural causes. The effect on structures, however is similar; consequently, the damage probability matrices (DPM) were developed without differentiation. The details of the hazard models are presented in Section 3.2.

A damage algorithm based on the probability damage matrix concept was developed using a survey technique similar to the approach used for fire. The details of the damage algorithm are given in Section 3.3. The survey results are given in Appendix B.

The exposure (i.e., assets exposed) data required for the wind hazard is identical to that required for the other hazards. The details of this facet of the methodology are given in Section 9.

The vulnerability data is information required by the hazard model for determination of expected damage. A special inspection form has been developed to collect this information

Table 3-1. Information Requirements for Wind

HAZARD AND DAMAGE	DATA SOURCE
Hazard Model	
Intensity/Probability Relation • Tornado • Severe Wind • Hurricane	Developed In-House
Structural Damage	
Probability Damage Matrices • One to Three Story, Wood Frame, Residential (A)* • One to Three Story, Concrete or Masonry Wall, Residential (B) • One to Three Story, Wood Frame, Commercial and Industrial (C) • One to Three Story, Concrete or Masonry Wall, Commercial and Industrial (D) • One to Three Story, Metal, Commercial and Industrial (E) • Four or More Story, Concrete or Masonry Structures Without Shear Wall or Ductile Frame (F) • Four or More Story, Concrete or Masonry Structures with Shear Wall or Ductile Frame (G) • Four or More Story, Steel Structures with Ductile Frame (H) • Mobile Homes Without Engineered Tie Downs • Mobile Homes with Engineered Tie Downs	Survey of Experts [3-20]
Effect of UBC Design Level	Survey of Experts
Effect of Airborne Water	Lacking (Not Considered)
Contents Damage	
Related to Structural Damage • Damageability of Contents	Use Earthquake Relationship

* Letters in parenthesis correspond to code used in methodology flow chart (Figure 3-13).

Table 3-1. Information Requirements for Wind (Continued)

HAZARD AND DAMAGE	DATA SOURCE
Life Loss	
Casualty Rate	Lacking (see Section 3.4.2)
Mission Reliability	
Damage Level Assigned to Mission Failure	Assigned (Building failed if damage exceeds 20 percent)

EXPOSURE AND VULNERABILITY	DATA SOURCE
Building	
Structure Age ● Proposed ● Existing	Base Inspection
Type of Construction ● One to Three Story, Wood Frame, Residential (A) ● One to Three Story, Concrete or Masonry, Residential (B) ● One to Three Story, Wood Frame, Commercial and Industrial (C) ● One to Three Story, Concrete or Masonry, Commerical and Industrial (D) ● One to Three Story, Metal (non-steel), Commercial and Industrial (E) ● Four or More Story, Concrete or Masonry Structures, No Shear Wall or Ductile Frame (F) ● Four or More Story, Concrete or Masonry Structures, With Shear Wall or Ductile Frame (G) ● Steel Structures, With Ductile Frame (regardless of height) (H) ● Mobile Homes, No Engineered Tie Downs ● Mobile Homes, With Engineered Tie Downs	Base Inspection
Design Level ● UBC Design Level 0, 1, 2, & 3	Base Inspection

Table 3-1. Information Requirements for Wind (Continued)

EXPOSURE AND VULNERABILITY	DATA SOURCE
Building (Continued)	
Is Mobile Structure Properly Anchored • Yes or No	Base Inspection
Number of Stories	Property Inventory
Value of Contents • Class 3 and 4 Property • Inventory Material • Minor Property • Commissary and Exchange Property • Special Services Property • Clubs, Other	Property Control Offices
Is Structure Waterproofed for Airborne Water • Yes or No	Base Inspection
Mission Assignments	Base Functional Charts

MITIGATIONS AND COST	DATA SOURCE
Cost Data	
Construction Cost	
• Replacement Cost for Existing Structure • Original Cost for Proposed Structure	Property Inventory
Mitigation Cost Factors for Proposed Structure • Designing Structural and Non-Structural Systems for Higher Wind Loading	
Steel Structure • UBC Level 1, 2, & 3 • Windows	MIT-CE-R72-20[3-15]
Reinforced Concrete Structure • UBC Level 1, 2, & 3 • Windows	MIT-CE-R72-20[3-15]
Ordinary Wood Frame • UBC Level 1, 2, & 3 • Windows	SEAOC Proceedings 1970 [3-16]

Table 3-1. Information Requirements for Wind (Continued)

MITIGATIONS AND COST	DATA SOURCE
Cost Data (Continued)	
Mitigation Cost Factors for Existing Structure (Continued)	
• Cost Factor for Anchoring	Telephone Survey
• Cost Factor for Waterproofing Against Airborne Water	BCF, 1972 [3-13]

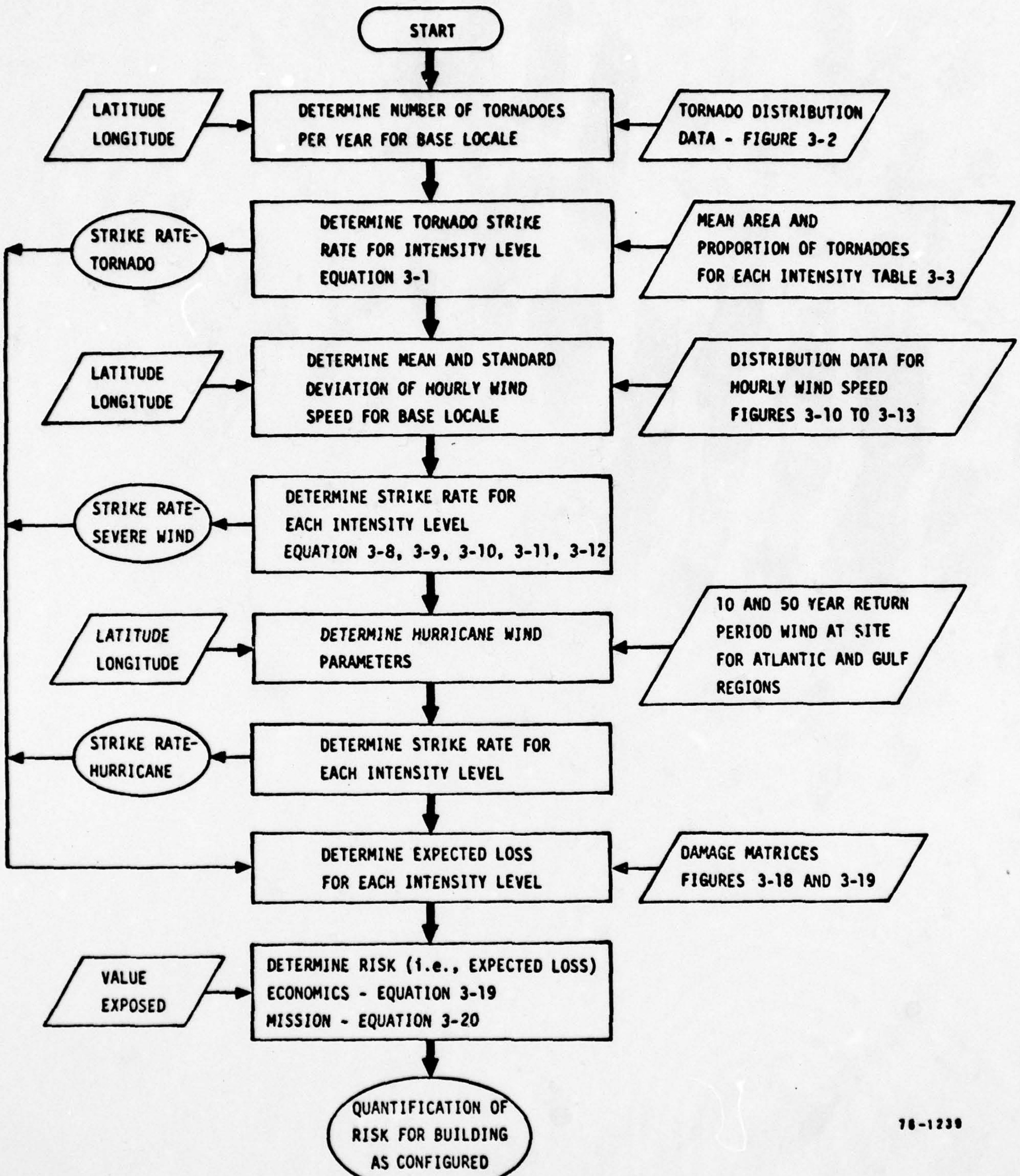

Figure 3-1. Risk Calculation for Wind Hazard

(Section 7). Vulnerability information is required for both the structure and its contents. The mitigations and their associated cost are discussed in Section 8.

3.2 Hazard Models

3.2.1 Tornado

Tornadoes are generally defined as violently rotating columns of air in contact with the ground. The tornado is visible as a condensation funnel that extends downward from the cloud base or as a rotating dust cloud rising from the ground. As the storm system moves, one or more tornadoes may form at intervals along the path, travel a few miles, lift and then reappear further down along the track. Small vortices may travel around a main tornado axis with as many as five of these satellite vortices having been observed in a tornado at one time. The tornado's main vortex has tangential, radial, and vertical air flow and an associated atmospheric pressure drop.

Tornadoes may form in association with squall lines or with thunderstorms accompanying frontal passages. They may also form with isolated thunderstorms not directly associated with frontal passages and in connection with hurricanes.

Formation of the strongest tornadoes usually requires the presence of three meterological conditions:

(1) a low level of moist, warm air surmounted by an upper level layer of cool dry air,

(2) narrow bands of strong winds in both the low level and upper level air layers, and

(3) a triggering mechanism.

Conditions one and two represent a potentially unstable atmosphere, which when disturbed by condition three may become

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unstable. This instability results in the generation of a severe storm which may spawn one or more tornadoes.

The damage caused by tornadoes is primarily due to wind and pressure forces causing partial or complete structural failure of the building.

In addition to wind and pressure related forces, damage is also caused by tornado induced missiles, which may range in size from roof gravel to automobiles. Penetration of roofs and walls, as well as instability or collapse of structures, may be produced by tornado induced missiles.

Annual occurrences and distribution of tornadoes are now being routinely tabulated by utilizing the rating system introduced by Fujita (Table 3-2). The FPP scale classifies the relative strength and size of tornadoes based on observed damage. The path of the tornado may be more than a mile (1.6 km) in width, but generally affects areas from 1/8 to 3/4 mile wide (0.2 to 1.2 km). The path is seldom more than 10 miles (16 km) long, although extreme cases are on record where the path of the storm extended for more than 200 miles (322 km).

The occurrence of tornadoes in the United States has been studied by several authors [3-2 to 3-5]. Of particular note are two studies. Thom [3-21] divided the United States into 1° by 1° grids and counted, for the years 1953-1962, the number of tornadoes in each grid. Fujita [3-5] performed a similar study for tornadoes occurring during the years 1955-1957, Pautz [3-4] did a similar study and covered the period 1955-1967. [See Figure 3-2]. The risk study performed here utilizes the Pautz occurrence data because of its 1° by 1° regionalization format and greater time span. This

Table 3-2.

TABLE OF FUJITA-PEARSON TORNADO SCALE. Characteristics of a tornado can be expressed as a combination of Fujita-scale windspeed and Pearson-scale path length and width. This scale permits us to classify tornadoes between two extreme FPP scales, 0,0,0 and 5,5,5. [3-1]

F-scale Maximum Windspeed				P-scale Path Length			P-scale Path Width			
Scale	mph	kts	m/s	Scale	miles	km	Scale	ft	yds	meters
F 0.0	40	35	18	P 0.0	0.3	0.5	P 0.0	17	6	5
0.1	43	37	19	0.1	0.4	0.6	0.1	19	6	6
0.2	46	40	21	0.2	0.4	0.6	0.2	21	7	6
0.3	49	43	22	0.3	0.5	0.7	0.3	24	8	7
0.4	52	46	23	0.4	0.5	0.8	0.4	26	9	8
0.5	56	48	25	0.5	0.6	0.9	0.5	30	10	9
0.6	59	51	26	0.6	0.6	1.0	0.6	33	11	10
0.7	63	54	28	0.7	0.7	1.1	0.7	37	13	11
0.8	66	57	30	0.8	0.8	1.3	0.8	42	14	13
0.9	70	60	31	0.9	0.9	1.4	0.9	47	16	14
F 1.0	73	64	33	P 1.0	1.0	1.6	P 1.0	53	18	16
1.1	77	67	34	1.1	1.1	1.8	1.1	59	20	18
1.2	81	70	36	1.2	1.3	2.0	1.2	66	22	20
1.3	84	73	38	1.3	1.4	2.3	1.3	74	25	23
1.4	88	77	40	1.4	1.6	2.6	1.4	84	28	26
1.5	92	80	41	1.5	1.8	2.9	1.5	94	31	29
1.6	96	84	43	1.6	2.0	3.2	1.6	105	35	32
1.7	100	87	45	1.7	2.2	3.6	1.7	118	39	36
1.8	104	91	47	1.8	2.5	4.0	1.8	133	44	40
1.9	109	94	49	1.9	2.8	4.5	1.9	149	50	45
F 2.0	113	98	50	P 2.0	3.2	5.1	P 2.0	167	56	51
2.1	117	102	52	2.1	3.5	5.7	2.1	187	62	57
2.2	121	105	54	2.2	4.0	6.4	2.2	210	70	64
2.3	126	109	56	2.3	4.5	7.2	2.3	235	78	72
2.4	130	113	58	2.4	5.0	8.1	2.4	265	88	81
2.5	135	117	60	2.5	5.6	9.0	2.5	297	99	90
2.6	139	121	62	2.6	6.3	10.2	2.6	333	111	102
2.7	144	125	64	2.7	7.1	11.4	2.7	374	125	114
2.8	148	129	66	2.8	7.9	12.8	2.8	419	140	128
2.9	153	132	68	2.9	8.9	14.3	2.9	470	157	143
F 3.0	158	137	70	P 3.0	10.0	16.1	P 3.0	528	176	161
3.1	162	141	73	3.1	11.2	18.0	3.1	591	197	180
3.2	167	145	75	3.2	12.6	20.3	3.2	665	222	203
3.3	172	149	77	3.3	14.1	22.7	3.3	744	248	227
3.4	177	154	79	3.4	15.9	25.6	3.4	837	279	256
3.5	182	158	81	3.5	17.8	28.6	3.5	940	313	286
3.6	187	162	83	3.6	20.0	32.2	3.6	1054	351	322
3.7	192	167	86	3.7	22.4	36.0	3.7	1183	394	360
3.8	197	171	88	3.8	25.1	40.4	3.8	1326	442	404
3.9	202	175	90	3.9	28.2	45.4	3.9	1489	496	454
F 4.0	207	180	93	P 4.0	31.6	50.9	P 4.0	1670	557	509
4.1	212	184	95	4.1	35.5	57.1	4.1	1874	625	571
4.2	218	189	97	4.2	39.8	64.1	4.2	2102	701	641
4.3	223	194	100	4.3	44.7	71.8	4.3	2354	785	718
4.4	228	198	102	4.4	50.1	80.6	4.4	2646	882	806
4.5	233	203	104	4.5	56.2	90.4	4.5	2967	989	904
4.6	238	207	107	4.6	63.1	102	4.6	3332	1111	1.0 km
4.7	244	212	109	4.7	70.8	114	4.7	3738	1246	1.1
4.8	250	217	112	4.8	79.4	128	4.8	4194	1398	1.3
4.9	255	222	114	4.9	89.1	143	4.9	4704	1568	1.4
F 5.0	261	227	117	P 5.0	100	161	P 5.0	1.0 mi	1760	1.6
5.1	267	232	119	5.1	112	181	5.1	1.1	1971	1.8
5.2	272	236	122	5.2	126	203	5.2	1.3	2218	2.0
5.3	278	241	124	5.3	141	227	5.3	1.4	2402	2.3
5.4	284	246	127	5.4	159	255	5.4	1.6	2798	2.6
5.5	289	251	129	5.5	178	286	5.5	1.8	3133	2.9
5.6	295	256	132	5.6	200	321	5.6	2.0	3520	3.2
5.7	301	261	135	5.7	224	360	5.7	2.2	3942	3.6
5.8	307	267	137	5.8	251	404	5.8	2.5	4418	4.0
5.9	313	272	140	5.9	207	454	5.9	2.8	4963	4.5

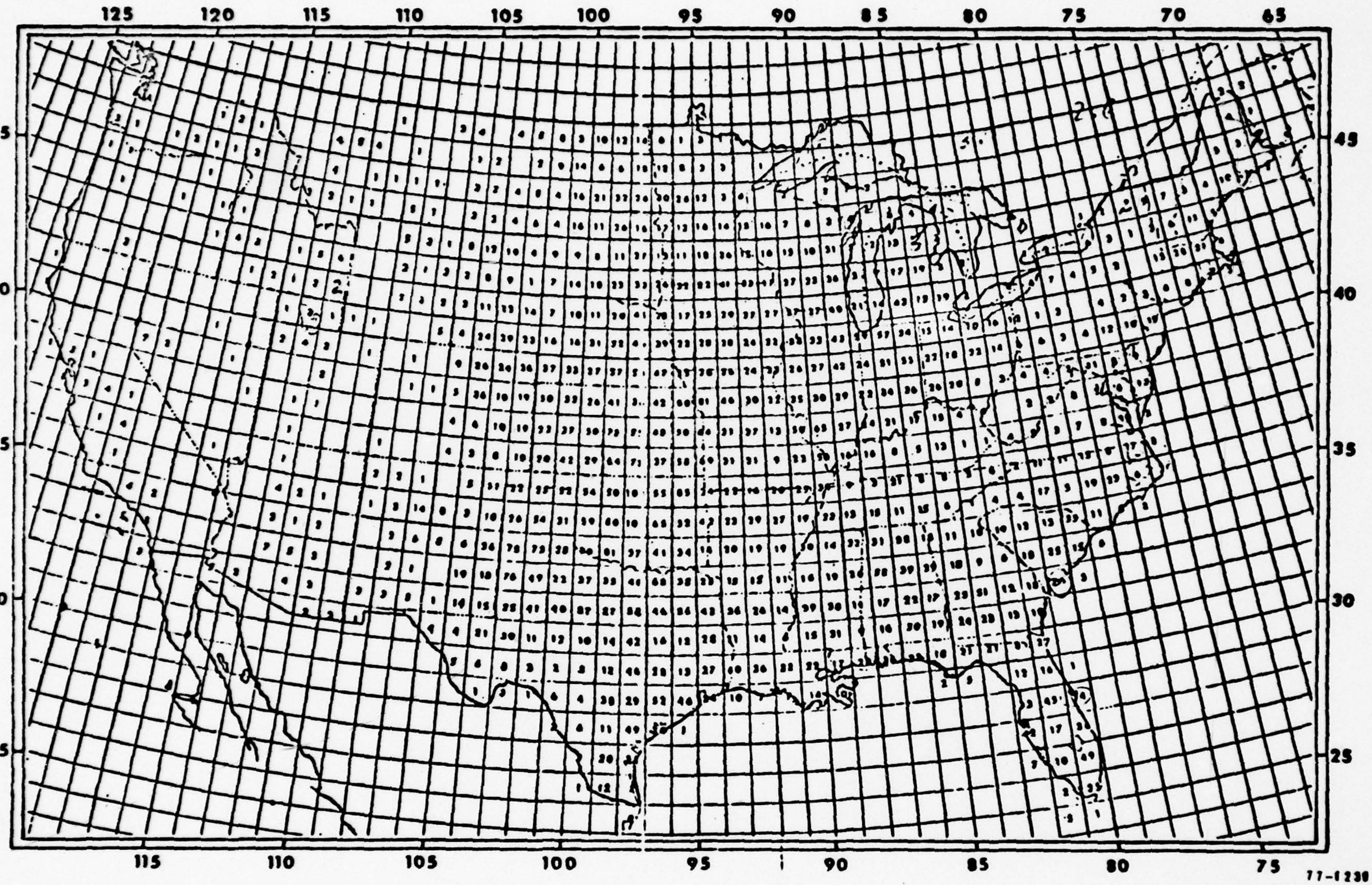

Figure 3-2. Total Number of Tornadoes within One-Degree Squares in the Contiguous United States for 1955-1967 [3-7]

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format is convenient for this study and is also consistent with the approach taken in counting earthquake occurrence.

Not all tornadoes are of the same intensity or size. As a result, a classification system has been developed so as to record in a systematic and exact manner tornado characteristics. This classification system is called the FPP Classification System (Table 3-2). We shall use these six classifications as our primary measure of hazard intensity. Since 1971, tornadoes have been classified using the FPP system. Therefore, it is possible, using recent data, to relate tornado occurrence to maximum wind velocity. Table 3-3, using 1971 and 1972 statistics [3-3, 3-7], shows that the majority of observed tornadoes are in the F1 and F2 classes.

Table 3-3. Tornado Occurrence and Area for Contiguous United States

FUJITA CLASSIFICATION	i	MAXIMUM WIND VELOCITY (MPH)	PROPORTION OF* OBSERVED TORNADOES IN CLASSIFICATION-R_i	MEAN TORNADO AREA* BY CLASSIFICATION (SQ. MI.)-A_i
F0	1	40-72(56)**	.199	0.02
F1	2	73-112(93)	.440	0.27
F2	3	113-157(135)	.266	1.72
F3	4	158-206(182)	.072	8.00
F4	5	207-260(234)	.021	28.36
F5	6	261-318(290)	.002	83.90

*Based on Reference 3-1.
**Based on Reference 3-20.
***Simple average maximum wind speed; wind speeds are in fastest 1/4 mile.

Implicit in Table 3-3 are two approximations which, based on recent data, may not be exactly correct. The first approximation is that the distribution of tornadoes with size, R_i, does not vary from region to region. The second approximation is that the entire area associated with a particular Fujita classification experiences the wind speed corresponding to that classification. The first assumption should be removed when sufficient data becomes available to develop valid regional distributions. The same is true for the second assumption. The error introduced by these two approximations is probably small, particularly for the second where a decrease in area for one classification will cause an increase in the probability associated with the next lower classification.

The occurrence statistics (Figure 3-2) give the mean number of tornadoes in each 1° by 1° region. When a tornado occurs in this region, it does not necessarily hit a particular structure. Therefore, the Tornado Strike Probability must be determined. This is defined to be the probability of a tornado hitting a point in any year and is calculated using the following equation:

$$\lambda_{i1} \doteq P_{i1} = \left(\frac{A_i}{A_o}\right) R_i N_t \qquad (3\text{-}1)^*$$

where

P_{i1} = Tornado Strike Probability for i^{th} classification.

---

*The strike rate, λ_i, used later in Equations (3-19) and (3-14) is approximately equal to P_i. For a Poisson Process, the probability in a short time Δt is equal to $\lambda_i \Delta t$. Thus $P_i \doteq \lambda_i \Delta t \doteq \lambda_i$ provided Δt = 1 year is small compared to the return period, $1/\lambda_i$.

A_i = mean area of tornado in i^{th} classification

A_o = area of 1° by 1° region around subject facility

N_t = mean number of tornadoes per year in the 1° by 1° region

R_i = proportion of tornadoes in i^{th} classification

N_t is obtained from Figure 3-2, while A_i and R_i are given in Table 3-3. Alternately, the ratio N_t/A_o may be taken from the most up-to-date Fujita contour map available giving the mean rate of occurrence per square mile per year.

The parameters given in Table 3-3 are based on recent FPP classification statistics. Previously Thom [3-2] observed that the mean area of all observed tornadoes was 2.82 square miles (with a significant standard deviation). If this average tornado area were used instead of the areas given in Table 3-3, the probability of being hit by a tornado would be much larger.

For example, the total probability of being hit by a tornado, based on the Fujita [3-1] data, is

$$P = \sum_{i=1}^{6} P_i = \frac{N_t}{A_o} \sum_{i=1}^{6} A_i R_i = 0.339 \frac{N_t}{A_o} \qquad (3-2)$$

while the total probability using Thom's mean area is

$$P = 2.82 \frac{N_t}{A_o} \qquad (3-3)$$

These probabilities differ by a factor of 8. This has been pointed out to illustrate the present uncertainty in the state-of-the-art with respect to the tornado hazard.

3.2.2 Severe Wind

Background

The degree to which a structure is subject to wind loading depends primarily on two parameters: the height above ground and the terrain roughness.

The magnitude of the mean velocity increases with height and the rate of increase is very much influenced by the roughness of the terrain. The variation of velocity with height is gradual. At heights great enough for the wind to be virtually independent of surface friction, the wind moves freely under the influence of the pressure gradient and attains the so-called gradient velocity. The height at which this occurs is called the gradient height. Figures 3-3 and 3-4 show typical velocity and mean velocity profiles. In the latter, the nominal gradient wind speed is 100 m.p.h. This shows that the wind speed at 100 feet in a city is approximately one-quarter of that in open country. The variations of velocity with height described in Figure 3-4 are power laws of the form

$$\frac{V_z}{V_g} = \left(\frac{z}{z_g}\right)^{\alpha} \qquad (3\text{-}4)$$

in which V_z is the velocity at height z, and V_g is the gradient velocity at height z_g.

An alternative representation for variations of velocity with height is the logarithmic law which can be written in the form

$$\frac{V_z}{V_g} = \frac{1}{k} C_g \log\left(\frac{z}{z_o}\right) \qquad (3\text{-}5)$$

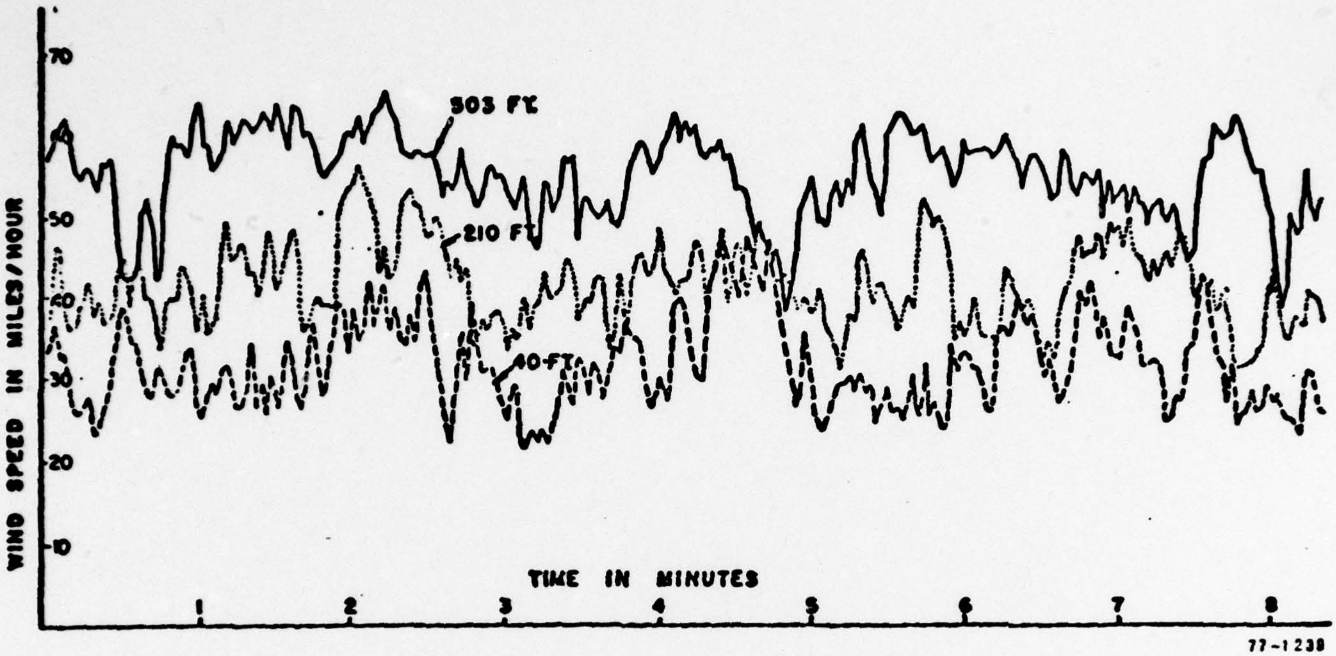

Figure 3-3. Record of Wind Speed at Three Heights on a 500 ft. Mast [3-24]

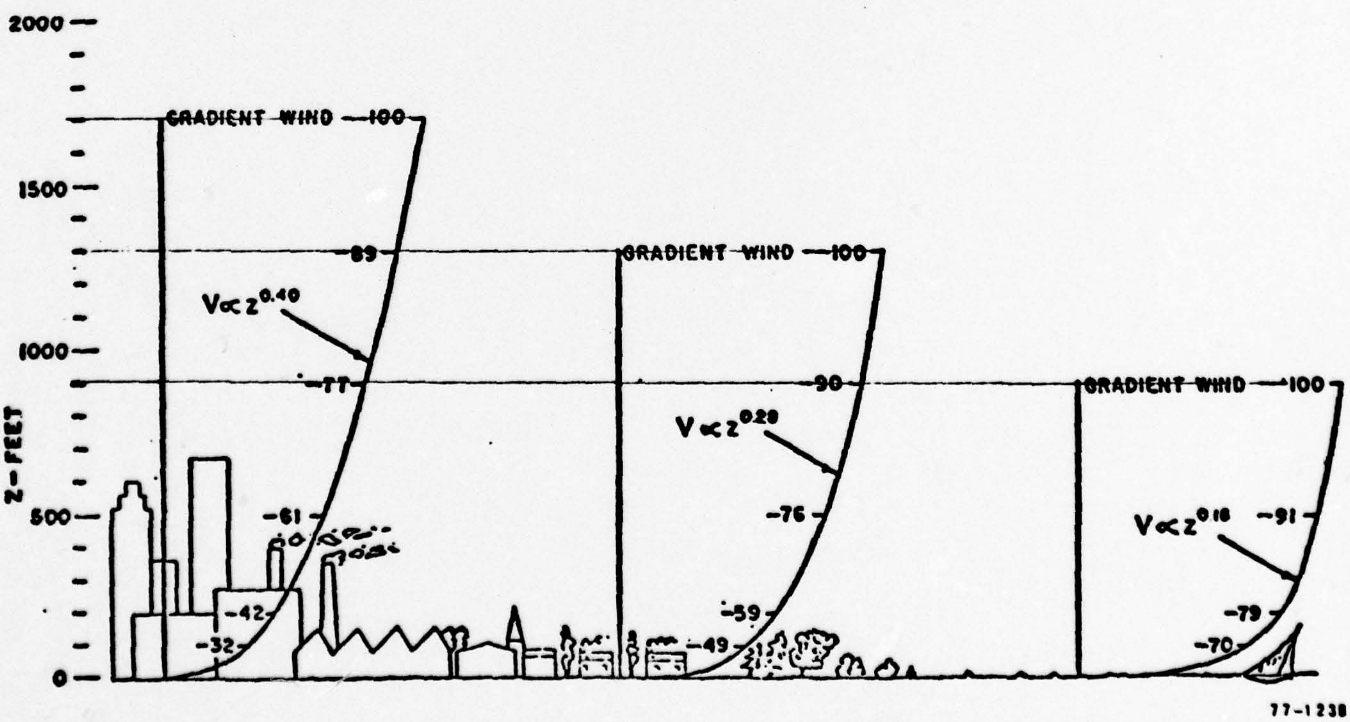

Figure 3-4. Profiles of Mean Wind Velocity over Level Terrains of Differing Roughness [3-24]

where C_g is the so called geostrophic drag coefficient, z_o is the roughness length of the surface, and k is von Karman's constant ≈ .40. The value of C_g can be estimated from

$$C_g \approx .16 \left(\frac{V_G}{f_c z_o}\right)^{-.09} \tag{3-6}$$

where f_c = Corish parameter = $1.452 \times 10^{-4} \sin \lambda \ \mathrm{sec}^{-1}$ where λ is the latitude. Representative values of the roughness length z_o are shown below

Properties of Mean Velocity Profiles in the
Atmospheric Boundary Layer

EXPOSURE	TERRAIN	ROUGHNESS LENGTH (Z_o) MILE	POWER LAW EXPONENT(d)		GRADIENT HEIGHT FEET (Z_g)	
			RANGE	USE HERE	RANGE	USE HERE
A	City Center	.01 - .05	.3 - .5	1/3	1500 - 1800	1500
B	Forest, Suburan	.30 - 1.00	.20 - .28	1/4.5	1100 - 1300	1200
C	Open Country	1.00 - 3.0	.10 - .16	1/7	600 - 950	900

An extreme wind characterization of the U.S. has been done by Thom [3-8]. In this July 1968, ASCE Structural Division Journal, Thom utilized wind data from 138 airport or open country stations to develop maps of wind velocities for 2-yr, 10-yr, 25-yr, 50-yr, and 100-yr mean recurrence intervals (return periods). Twenty-one years of data were used in this study. Alaska, Hawaii, Puerto Rico as well as the continental United States were considered. The wind speeds correspond to an open country exposure (i.e., 1/7 power law exposure) and are for the standard level of 30 ft. Figures 3-5 to 3-9 and Tables 3-4 and 3-5 show Thom's results.

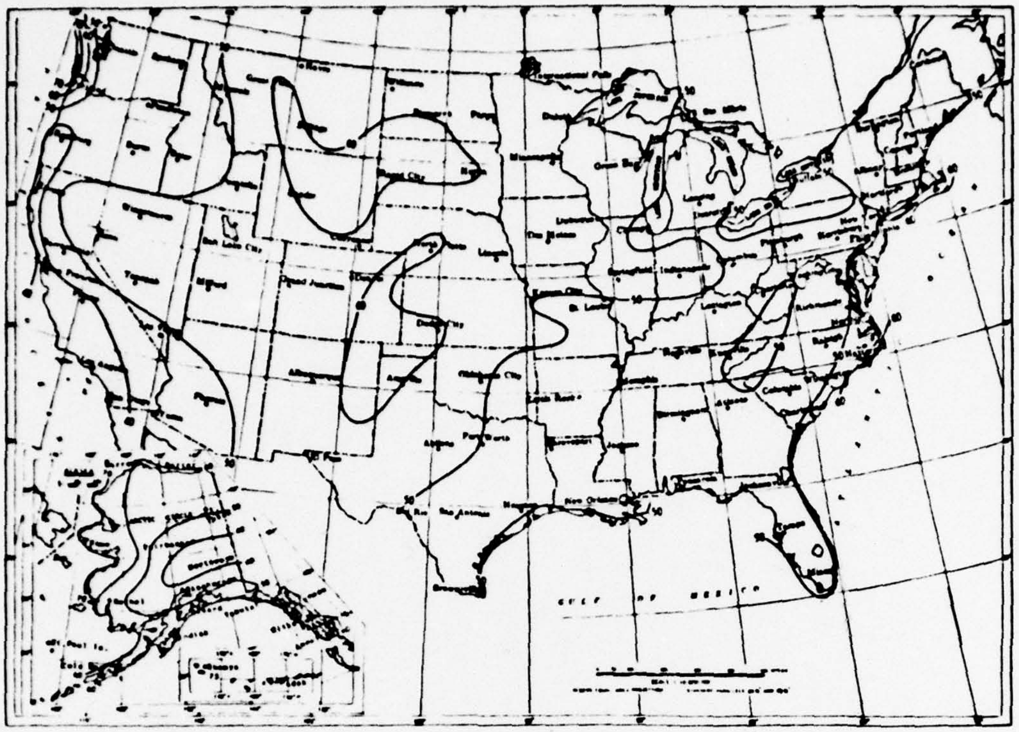

Figure 3-5. Isotach 0.50 Quantiles, in Miles Per Hour: Annual Extreme-Mile 30 Ft. Above Ground, 2-Yr. Mean Recurrence Interval [3-8]

77-1238

Figure 3-6. Isotach 0.10 Quantiles, in Miles Per Hour: Annual Extreme-Mile 30 Ft. Above Ground, 10-Yr. Mean Recurrence Interval [3-8]

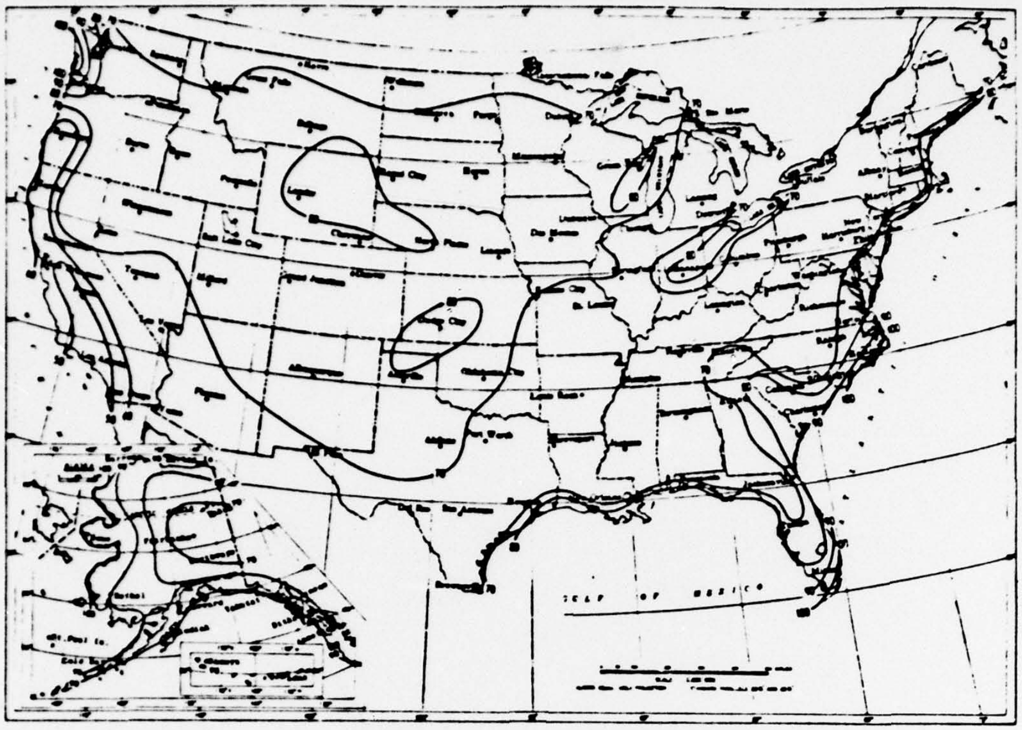

Figure 3-7. Isotach 0.04 Quantiles, in Miles Per Hour: Annual Extreme-Mile 30 Ft. Above Ground, 25-Yr. Mean Recurrence Interval [3-8]

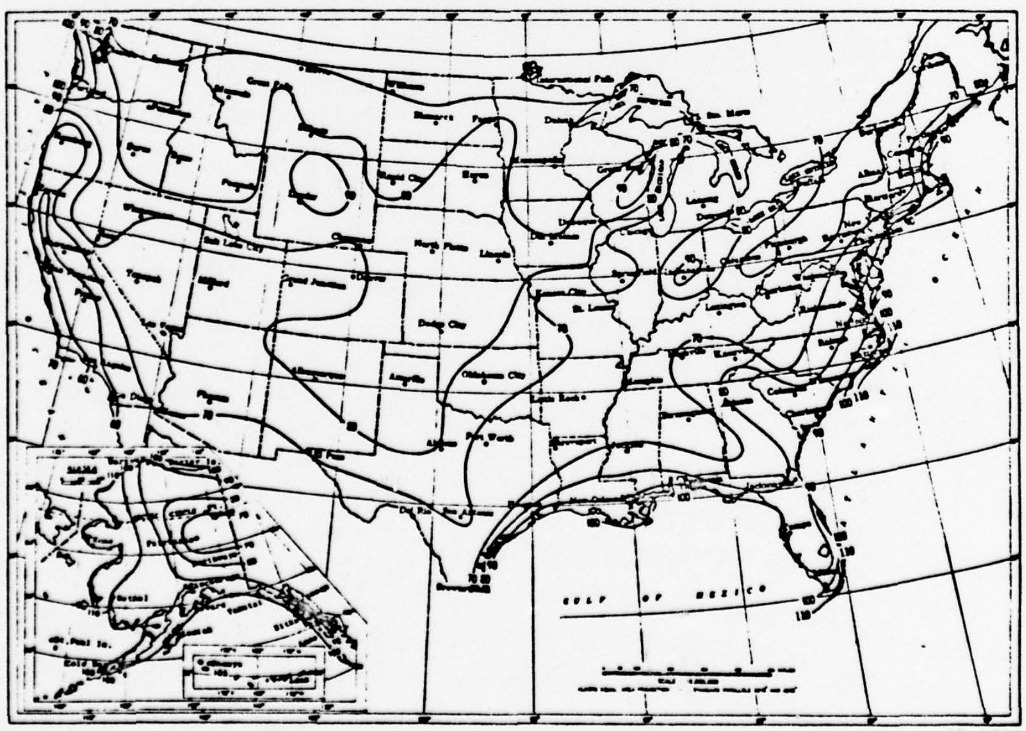

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Figure 3-8. Isotach 0.02 Quantiles, in Miles Per Hour: Annual Extreme-Mile 30 Ft. Above Ground, 50-Yr. Mean Recurrence Interval [3-8]

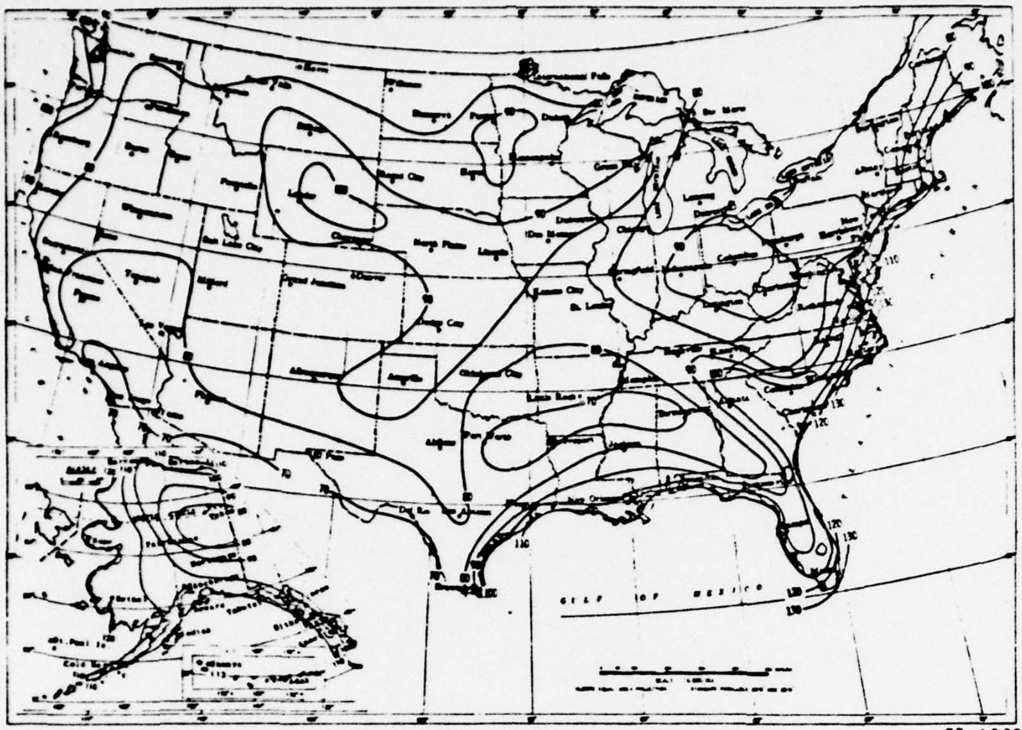

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Figure 3-9. Isotach 0.01 Quantiles, in Miles Per Hour: Annual Extreme-Mile 30 Ft. Above Ground, 100-Yr. Mean Recurrence Interval [3-8]

Table 3-4. Hawaii Fastest Mile Quantiles [3-8]

1-F(R) (1)	0.50 (2) (2)	0.10 (3) (3)	0.04 (25) (4)	0.02 (50) (5)	0.01 (100) (6)
LEEWARD EXPOSURE	38	51	60	67	75
WINDWARD EXPOSURE	42	59	70	80	91

Table 3-5. Puerto Rico Fastest Mile Quantiles [3-8]

1-F(R) (1)	0.50 (2) (2)	0.10 (10) (3)	0.04 (25) (4)	0.02 (50) (5)	0.01 (100) (6)
ANY EXPOSURE	45	65	80	95	110

A Fisher-Trippett Type II probability distribution (also referred to as a Frechet probability distribution) was selected by Thom. The analytical form of the cumulative probability distribution function for this distribution is

$$F_{II}(V) = \exp\left\{-[(V - \mu)/\sigma]^{-\gamma}\right\} \tag{3-7}$$

where V is the wind velocity and μ, σ, and γ are location, scale and tail length parameters, respectively. Thom chose to let $\mu = o$.

Although Tom's basic approach will not be utilized for this hazard, it has been discussed briefly because of its general acceptance in the filed of structures. The approach used by Thom is based on maximum annual wind speed data. Usually wind speeds appearing in codes are based on these statistics. Design wind speeds and associated wind speed return periods usually relate to maximum annual extreme winds. For example, from Figure 3-9 the 100 year wind velocity for Cheyenne, Wyoming, is 90 mph. This means that, on the average, once every one hundred years we can expect the maximum annual wind speed to be equal to or greater than 90 mph. This type of information is not in the correct form for predicting damage becasue it fails to prodcue the distribution of severe wind speeds. More wind speed information needs to be retained than the maximum wind speed for the year.

Prior to discussing the wind speed characterization used for estimating damage, consider the following example which shows the error in using the extreme annual wind speed data. In the study of tornado occurrence it was noted how Thom studied the

statistics of tornado occurrence for the years 1952 - 1962. During this ten year period he counted the total number of tornadoes which occurred in each 1° by 1° region of the U. S. Considering one such grid in Oklahoma the total was 50 tornadoes. This represents 50 pieces of information from which we can characterize in a statistical sense the properties of tornadoes. For example, we could determine how many tornadoes during this 10 year span had a wind velocity between 113 and 157 mph. Based on experience we would expect this number to be 10 to 15. Now if the same data were analyzed as extreme annual data then only the highest wind speed each year could be recorded and all other tornadoes ignored. Therefore, only 10 data points would exist and for this same region we would probably have one tornado each year above 157 mph. Thus, all information regarding the size distribution would be lost and hence our damage estimate would not reflect the large number of occurrences below the annual maximum wind speed even though these occurrences are still potentially damage producing.

The approach used here to estimate wind speeds for use in damage evaluation is based on maximum hourly wind speed data. Arguments of the type presented in the previous paragraph could of course be extended and one could rationalize that what we really want is peak gust velocities. However, we chose the hourly wind speed approach because peak gust data does not presently exist in a convenient form such as regionalized maps. Also the hourly observations seem to be of a short enough time duration so as to provide acceptable estimates and still remove the errors inherent in using only annual statistics of extreme winds. Contour maps of the hourly wind speeds are presented in Figures 3-10 through 3-13. Note that these data are for a point 50 feet above ground, not 30 feet as is usually the case.

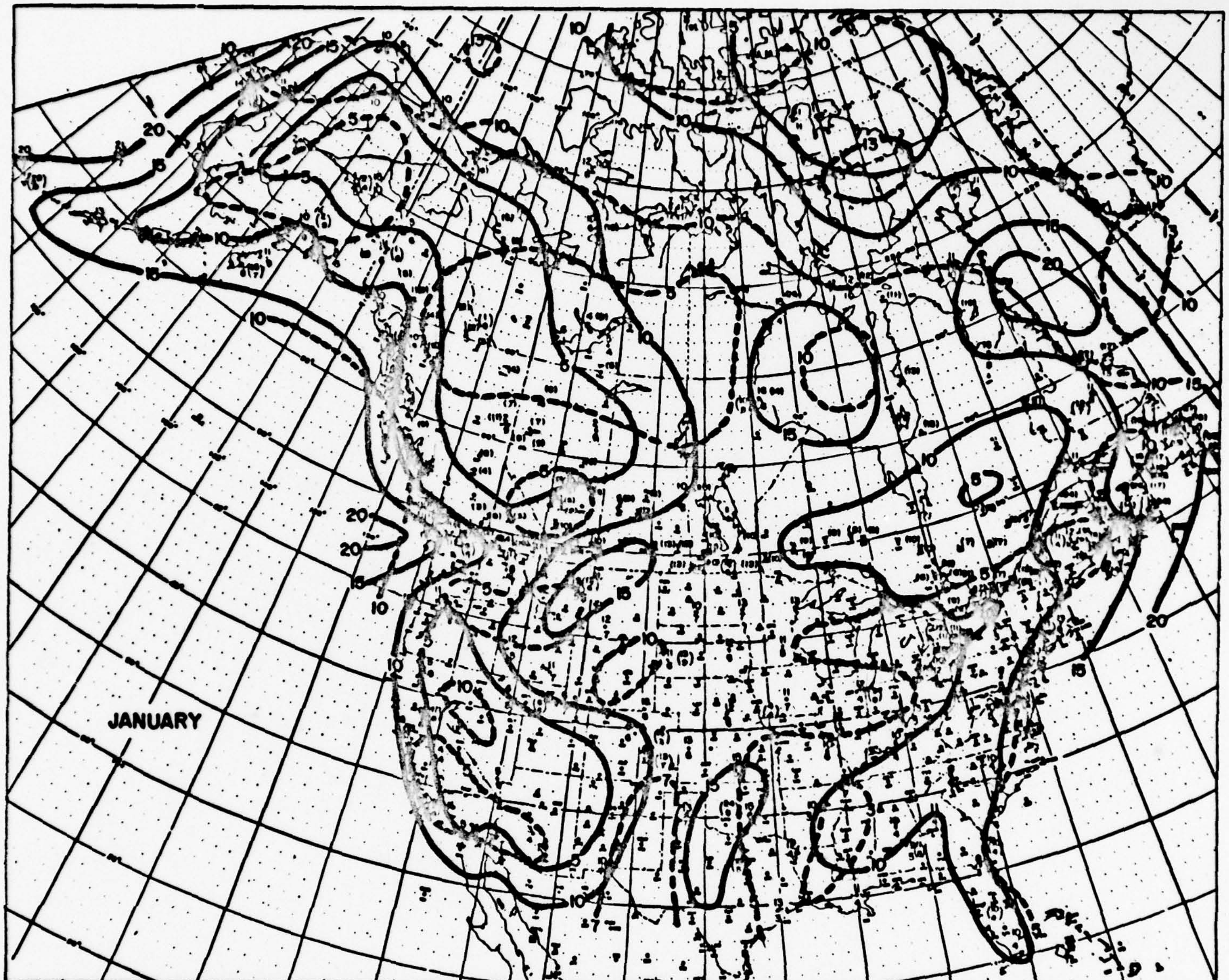

Figure 3-10. Hourly mean wind speed estimates (mile h^{-1}) for January, corrected to 50 ft. above ground. Isopleths of mean speed are in solid lines, standard deviation in broken lines. [3-14]

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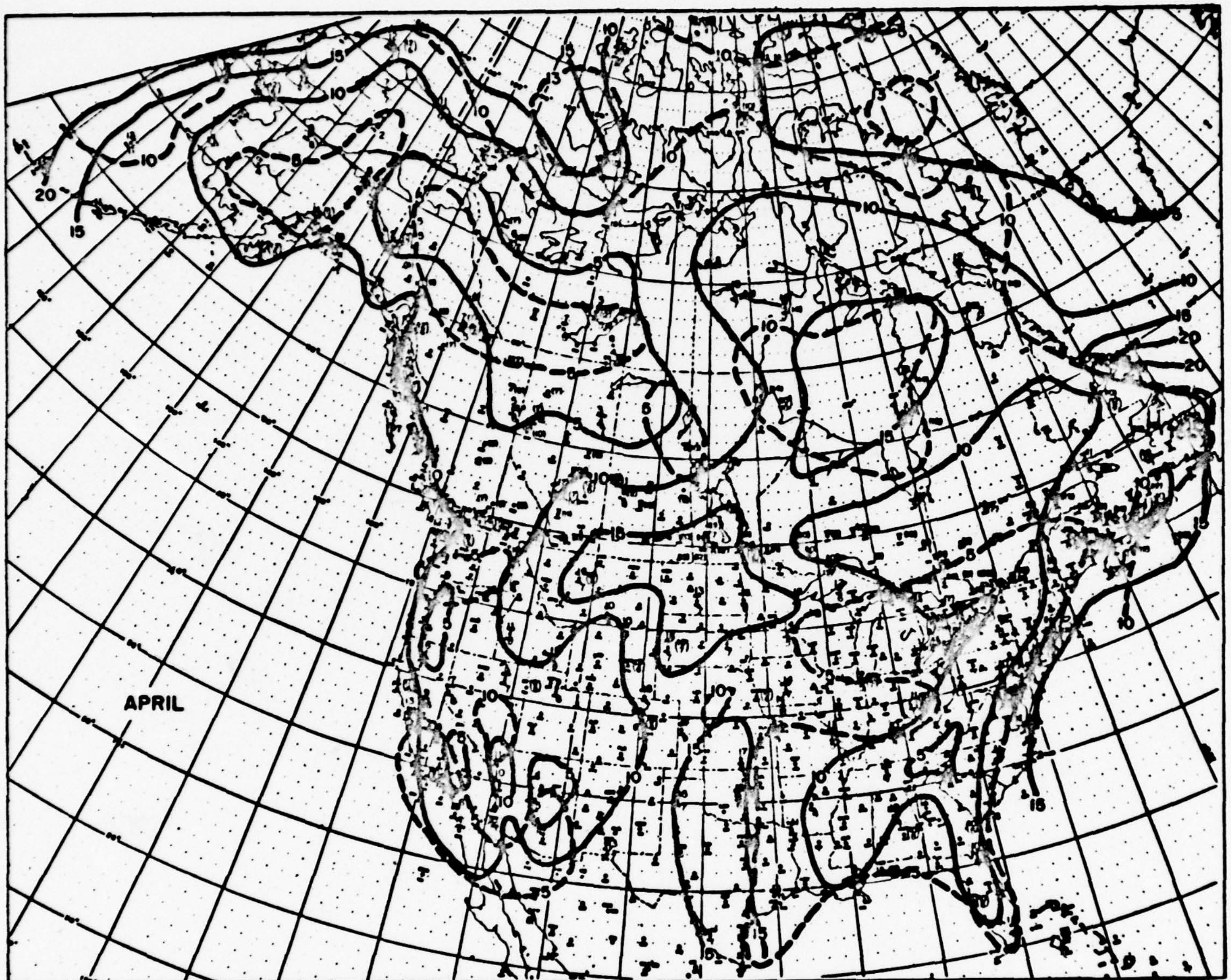

Figure 3-11. Hourly mean wind speed estimates (mile h^{-1}) for April, corrected to 50 ft. above ground. Isopleths of mean speed are in solid lines, standard deviation in broken lines. [3-14]

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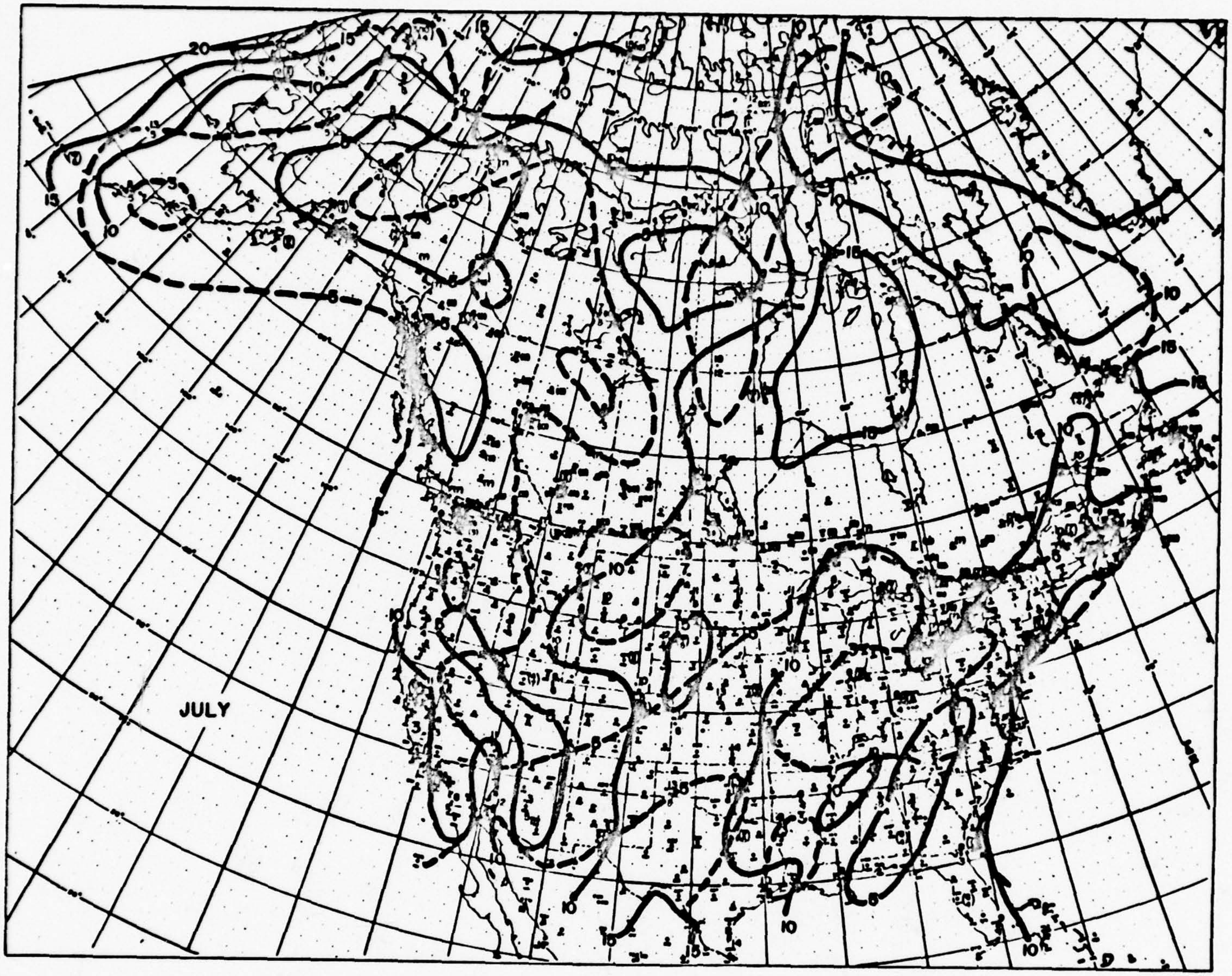

Figure 3-12. Hourly mean wind speed estimates (mile h^{-1}) for July, corrected to 50 ft. above ground. Isopleths of mean speed are in solid lines, standard deviation in broken lines. [3-14]

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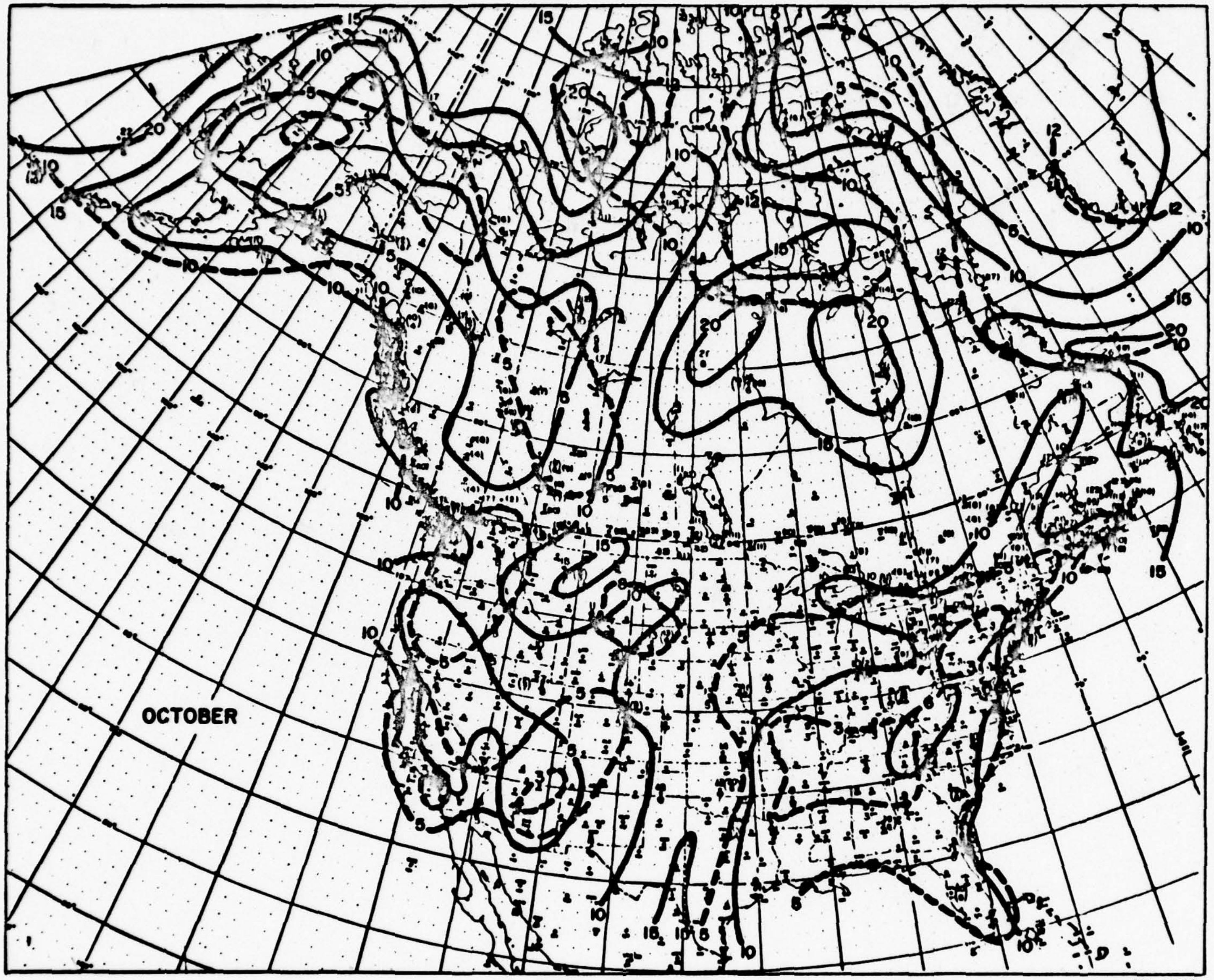

Figure 3-13. Hourly mean wind speed estimates (mile h^{-1}) for October, corrected to 50 ft. above ground. Isopleths of mean speed are in solid lines, standard deviation in broken lines. [3-14]

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The observation of wind speeds on an hourly basis has been conducted at over 150 stations. It has been observed that the hourly wind speed follows a Gamma distribution with a probability density function of the form[3-14].

$$f(y) = 0.5y^2 \; e^{-y} \tag{3-8}$$

where y is a reduced variate with mean 3 and standard deviation $\sqrt{3}$. This reduced variate is expressed in terms of the mean ($\bar{V}$) and the standard deviation (σ_v) of the hourly wind speed and is presented below

$$V_h = \bar{V} + \sigma_v \, y_s \tag{3-9}$$

where

$$y_s = (y-3)/\sqrt{3} \tag{3-10}$$

The cumulative distribution function corresponding to Equation 3-8 is

$$F(y) = \int_0^y f(x)dx = 1 - 0.5e^{-y}[y^2+2y+2] \tag{3-11}$$

Rearranging Equation (3-10) we obtain

$$y = 3 + \sqrt{3} \, y_s$$

and from Equation (3-9)

$$y_s = (V_h - \bar{V})/\sigma_v$$

therefore it follows, using Equation (3-11)

$$f(y) \Rightarrow f(V_h) = 0.5 \left\{ 3 + \left[\frac{\sqrt{3}(V_h - \bar{V})}{\sigma_v} \right] \right\}^2 \exp \left\{ 3 + \left[\frac{\sqrt{3}(V_h - \bar{V})}{\sigma_v} \right] \right\} \quad (3\text{-}12)$$

To demonstrate the use of these equations consider the site of Los Angeles, California. The January hourly wind has a mean of 9 mph and a standard deviation of 5 mph (Figure 3-10). In order to evaluate the probability of having an hourly wind speed below an arbitrary magnitude, say 30 mph, the cumulative distribution function (Equation 3-11) is used. It follows that, for Los Angeles

$$y_s = (30-9)/5 = 4.20$$

$$y = 3 + \sqrt{3}\, y_s = 10.27$$

$$F(y) = 1 - 0.5 e^{-y} [y^2 + 2y + 2]$$

$$= 1 - 2.218 \times 10^{-3}$$

Therefore, the probability that the wind speed in Los Angeles will be above 30 mph in any specific one hour period during January is

$$P\ [V > 30\text{mph}] = 2.218 \times 10^{-3}$$

An alternative interpretation is that the return period (in hours) of a greater than 30 mph wind speed is ($1/2.218 \times 10^{-3}$) or 451 hours. Since there are 744 hours in January we can expect, on the average, that there are 1.6 winds each January with speeds above 30 mph.

Figures 3-10 through 3-13 show contours of the mean and standard deviations of hourly wind speed for the continental U.S. and Alaska. The maps correspond to January, April, July, and October wind speed data[3-14]. In the damage prediction procedure the month preceeding and the month following each of these four mapped months are assumed to have the same statistical estimates of mean and standard deviation as the mapped month. Therefore, the number of appropriate exposure days for the maps are: January, 90 days [i.e., Dec. (31) + Jan.(31) + Feb. (28)]; April, 92 days; July, 92 days: and October, 91 days. In hours this is 2160, 2208, 2208, and 2184, respectively.

Carrying the Los Angeles example further using April, July and October data, it follows that

$$
\begin{aligned}
P[V_h > 30 \text{ mph}] &= 2.22 \times 10^{-3} \text{ (January)} \\
&= 1.24 \times 10^{-3} \text{ (April)} \\
&= 2.15 \times 10^{-3} \text{ (July)} \\
&= 1.24 \times 10^{-3} \text{ (October)}
\end{aligned}
$$

or corresponding return periods of

January = 451 hours
April = 806 hours
July = 465 hours
October = 806 hours

It then follows that each three month period has the following number of winds exceeding 30 mph:

December, January, February	:(2160/451)	= 4.74*
March, April, May	:(2208/806)	= 2.74
June, July, August	:(2208/465)	= 4.75
September, October, November	:(2184/806)	= 2.71
	Total	=14.99

Therefore, we can expect that the wind speed in Los Angeles will exceed 30 mph 15 times per year, on the average.

In general, we are not interested in the number of times each year that, on the average, the wind speed will exceed a certain level. Instead what we are interested in is the number of times each year that the wind speed is between two speed limits. Let V_L and V_U be two such limits with $V_L < V_U$. It then follows from Equation 3-11 that

$$\lambda_{i2} = \text{Rate } (V_L<V_h<V_U) = \text{Rate } (V_h>V_L) - \text{Rate } (V_h>V_U) \quad (3\text{-}13)$$

Figure 3-14 shows a schematic of the procedure used to obtain such interval rates (or alternately return period) estimates.

Elsewhere in this report, extensive use is made of the relationship $P_1 \doteq \lambda_i$ where P_i is the probability of having one or more events in one time unit (e.g. one year) and λ_i is the mean rate of events (e.g. number per year). This approximate relationship, however, only holds when $\lambda_i << 1$. Consequently, great care must be exercised in applying it to the

*In one-quarter of a year is 2200 hours practice.

severe wind hazard. On a yearly basis (no/yr) λ_i can easily be much greater than 1, as was demonstrated above. On an hourly basis (no/yr), however, this is not the case. Therefore the following approach must be used to determine the annual probability of occurrence.

Let λ_{i2} (no/hr, severe wind) $\triangleq P_i$ (Figure 3-14) as calculated with equations 3-12 and 3-13 for each quarter of the year.

Next find the probability of occurrence for each quarter using

$^{\alpha}P_{i2}$ = quarterly probability of occurrence, severe wind

$$= 1 - (1 - {}^{\alpha}\lambda_{i2})^N$$

where N = number of hours in quarter

QUARTER	α (Not an Exponent)	N
DEC - FEB	1	2160
MAR - MAY	2	2208
JUN - AUG	3	2208
SEP - NOV	4	2184

Lastly, the annual probability is given by

$$P_{i2} = 1 - \prod_{\alpha=1}^{4} (1 - {}^{\alpha}P_{i2}) \qquad (3\text{-}14)$$

This is equivalent to the Poisson Process relationship (equation 2-1) when N is large

where α = index for quarter of year
i = index for wind state

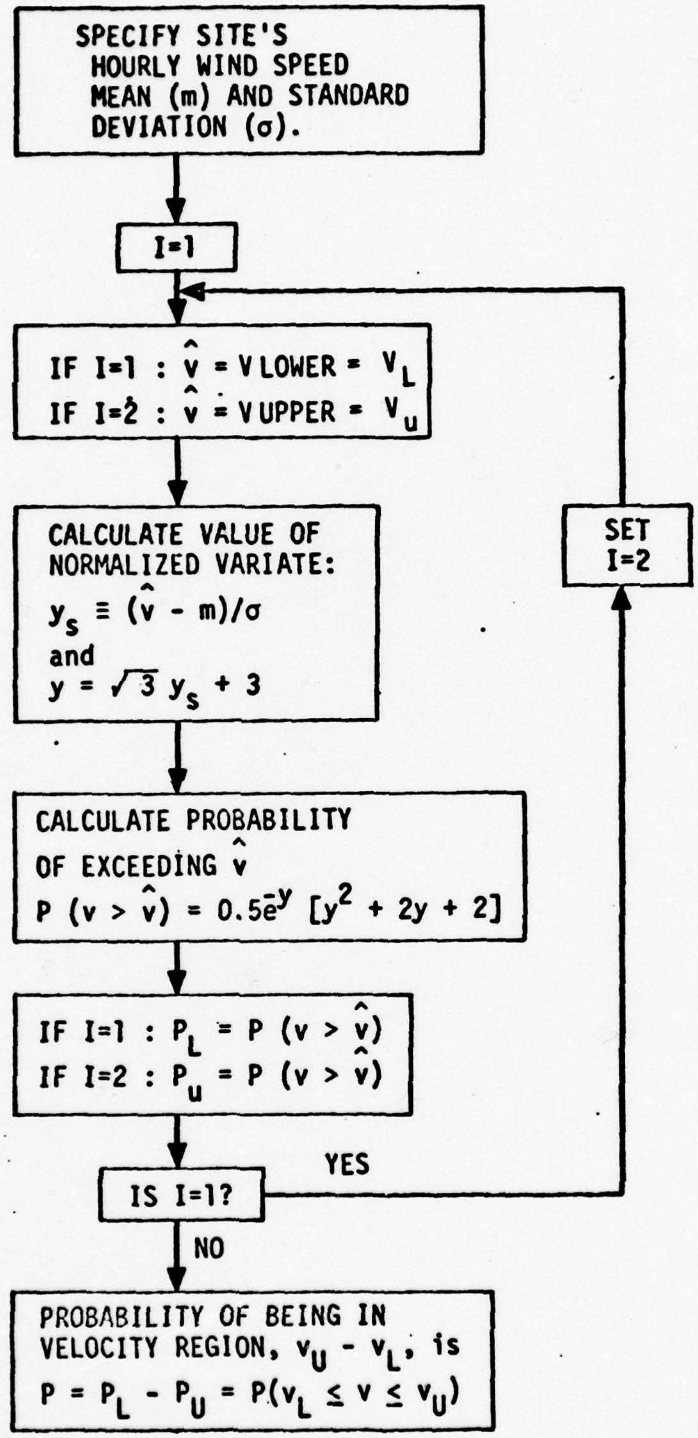

Figure 3-14. Schematic of Severe Wind Procedure

Proof: Let $\lambda = \frac{t}{N}$

then $(1 - \lambda)^N = (1 - \frac{t}{N})^N$

but $(1 - \frac{t}{N})^N \rightarrow e^{-t}$ for N large

thus $(1 - \lambda)^N \rightarrow e^{-\lambda N}$ for N large

thus $1 - (1 - \lambda)^N \rightarrow 1 - e^{-\lambda N}$ for N large

As stated above and shown in Section 3.3, in order to estimate damage it is necessary to calculate the probability of having wind velocities in certain specific ranges. More specifically, the damage matrices shown in Table 3-16 specify wind states of 1, 2, 3, etc. Therefore, one must specify a specific velocity range corresponding to each column of the damage matrix. These ranges are specified in Section 3.3.

The damage matrices are based on the wind velocity at the site, while the wind data is based on open country. The two will be the same only if the structure is located in open country. Otherwise the local terrain modifies the velocity that the building actually feels. To account for this effect a terrain factor has been developed [3-19]. Three types of exposure (i.e., factors) exist:

Exposure A - centers of large cities and very rough, hilly terrain

Exposure B - suburban areas, towns, city outskirts, wooded areas, and rolling terrain, parkland, rough coastal belts

Exposure C - open country, flat open coastal belts, grassland, prairie, tundra, small islands situated in large bodies of water

The equivalent open country velocity for exposures A and B is given by the following equations

<u>Exposure A</u>

$$V_{50}(c) = \text{Equivalent open-country velocity} = 2.056\ V_{site} \quad (3\text{-}15a)$$

<u>Exposure B</u>

$$V_{50}(c) = \text{Equivalent open-country velocity} = 1.341\ V_{site} \quad (3\text{-}15b)$$

These relationships were developed as follows:

The general equation used to calculate velocity as a function of height is given below[3-19]:

$$\left(\frac{V_z}{V_{50}}\right) = \left(\frac{z}{50}\right)^{\alpha} \quad (3\text{-}16)$$

where

z = height

V_z = wind velocity at height z

V_{50} = wind velocity at height 50 feet

α = power law coefficient

The coefficient for each exposure as well as the corresponding gradient height (the height above which the wind velocity is constant) is given in Table 3-6.

Table 3-6

EXPOSURE	α	z_g
A	1/3	1500
B	1/4.5	1200
C	1/7	900

First we calculate the gradient (or far field) velocity for open country (exposure C) using Equation 3-16; i.e.

$$V_g = V_{50}(C)\left(\frac{900}{50}\right)^{1/7}$$

where $V_{50}(C)$ *= velocity at 50 ft for exposure C.*

Then $V_{50}(B)$ is calculated (Equation 3-16)

$$\begin{aligned} V_{50}(B) &= V_g\left(\frac{50}{1200}\right)^{1/4.5} \\ &= V_{50}(C)\left(\frac{900}{50}\right)^{1/7}\left(\frac{50}{1200}\right)^{1/4.5} \\ &= 0.7458\ V_{50}(C) \end{aligned}$$

Repeating the procedure for exposure A and then inverting, yields the previously stated results (Equations 3-15a and 3-15b). The equivalent velocities for each value needed in the damage calculation are given in Table 3-7.

Table 3-7. Equivalent Open-Country Velocity

V_{SITE} AT 50 Ft	EQUIVALENT OPEN COUNTRY VELOCITY (AT 50 FT)		
	EXPOSURE		
	A	B	C
37.5	77.1	50.3	37.5
62.5	128.5	83.8	62.5
87.5	179.9	117.3	87.5
112.5	231.3	150.8	112.5
137.7	282.7	184.3	137.5
175	359.8	234.5	175
225	462.6	301.5	225
275	565.4	368.5	275
325	668.2	435.5	325

3.2.3 Hurricane Wind

General Description

Hurricanes are large cyclonic storms with 73 mph or greater winds flowing in a large spiral about a relatively calm center called the core, or eye. They are formed in the tropics, but have a translational motion that carries them, in many instances, into the northern latitudes. In the tropical North Pacific, such storms are called typhoons. While their frequency of occurrence is much less than that of tornadoes, the devastation associated with hurricanes is often times more widespread, bringing with them other hazards including strom surge, flooding, and even tornadoes.

Hurricanes differ from tornadoes in the following respects:

(1) The pressure drop associated with the passage of a hurricane over a structure is rather gradual and has very little effect on the structure. The rate of change of pressure associated with the passing of a tornado is, on the other hand, very large, causing some structures to literally explode.

(2) Hurricane maximum windspeed is usually much smaller than that of a tornado.

(3) While both storms are rotating air masses, the hurricane rotating air mass covers much more area than that of a tornado.

(4) The lifetime of a hurricane is measured in days whereas a tornado is measured in minutes.

(5) Vertical windspeeds in hurricanes are very low in comparison to tornadoes so that hurricanes have little capacity to hold aloft large heavy missiles; tornadoes have been reported to transport large objects considerable distances.

The intensity of a hurricane is proportional to (1) the hurricane's efficiency in evacuating warm air carried to the top of the hurricane and (2) the sea surface temperature. Since these parameters are seldom constant for protracted periods of time, the hurricane is continually adjusting to these external forces and therefore, its wind field is constantly changing.

The average life of a hurricane is about nine days, although it may vary from eight to twelve days. The factors which determine the lifetime of a hurricane are the time and place of origin and the general circulation features existing in the atmosphere at the time of occurrence. Few storms dissipate as long as they are over warm tropical waters. Those that form in the Carribean Sea and the Gulf of Mexico have shorter lives because the region of formation is near to land areas. As land is encountered, frictional effects of the land roughness alter the momentum and energy inflows resulting in a reduction in the maximum windspeed. When the windspeed drops below 73 mph, the hurricane is reclassified as a tropical storm.

Given that a tropical cyclone qualifies as a hurricane, its intensity is historically measured in terms of the central pressure at the core. The lower the central pressure, the more intense the hurricane. The pressure and windspeed are related through hydrometerological equations so that any pressure below 29.0 in. (982 millibars) has a theoretical windspeed greater than 73 mph.

Hurricane Occurrence

The approach taken herein for estimating the occurrence of wind speeds associated with hurricanes is exactly that proposed for nuclear reactor design (3-21). All factors involved in the problem (e.g., confidence in wind flow patterns around buildings, statistics of hurricane width, profile, etc.) when balanced lead to a reliance on actual measured extreme wind data. Therefore, the Frechet extreme wind model proposed by Thom (3-22) to characterize coastal region hurricane winds

is used. The Frechet cumulative probability distribution function $F(V > V_m)$ expresses the probability that a windspeed V will exceed a given windspeed V_m, thus

$$F(V > V_m) = \exp\left\{-[(V_m/\sigma)^{-\gamma}]\right\} = \frac{1}{R} \qquad (3\text{-}17)$$

where

R = return period
V = a specified windspeed
V_m = a pre-selected windspeed which will depend on the building's exposure as discussed in Section 3.2.2
σ = standard deviation
γ = tail length parameter for distribution

The corresponding return period, R, of windspeed, V, is the inverse of Equation (3-17). Thom uses this distribution to characterize the U.S., including the Atlantic and Gulf coastal regions, Hawaii, and Alaska (3-22). Figures 3-15 and 3-16 show the windspeeds for 10 and 50 year return periods. The value of the windspeed in these figures is the value for V_m in Equation (3-17), corresponding to the appropriate return period. A map of 1° by 1° grid cells of the United States was overlaid on Figure 3-16 to determine the coastal cells where windspeeds in excess of 73 mph occur. The result is shown in Figure 3-17, where the cross-hatched area represents all the grid cells within which hurricane force winds occur. They are assumed to be generated by hurricanes, so that the hurricane wind hazard is limited to the 3000 miles of coastline from Texas to Maine and does not include Hawaii or Alaska. This conclusion is consistent with the work of Ho, Schwerdt, and Goodyear [3-23].

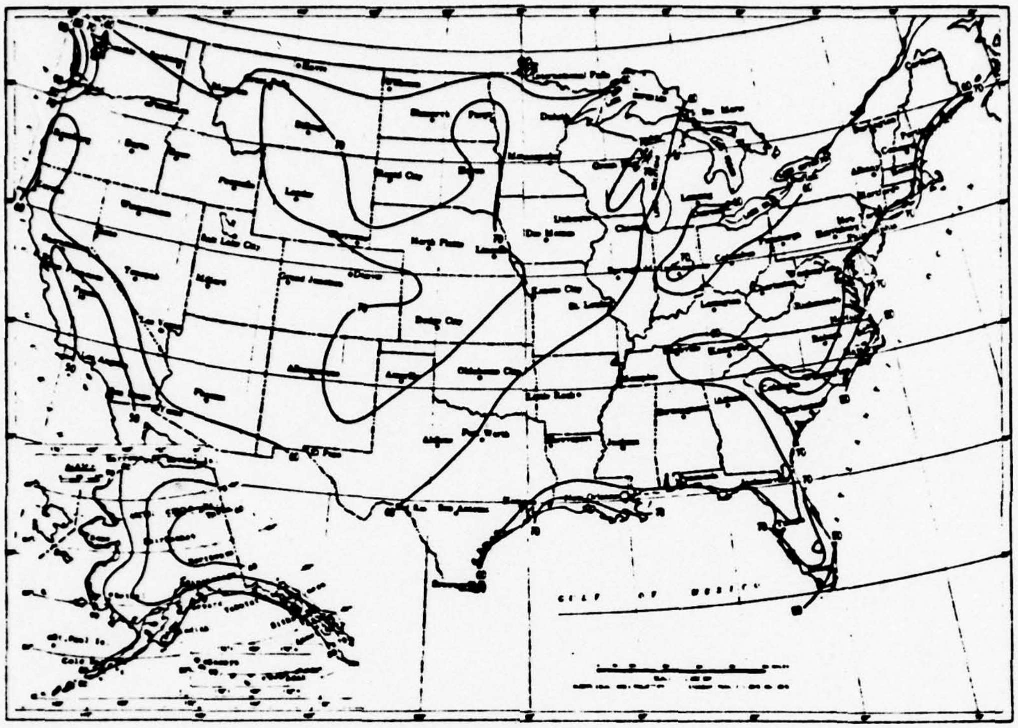

Figure 3-15. Isotach 0.10 Quantiles, in Miles Per Hour: Annual Extreme-Mile 30 Ft. Above Ground, 10-Yr. Mean Occurrence Interval [3-8]

Figure 3-16. Isotach 0.02 Quantiles, in Miles Per Hour: Annual Extreme-Mile 30 Ft. Above Ground, 50-Yr. Mean Occurrence Interval [3-8]

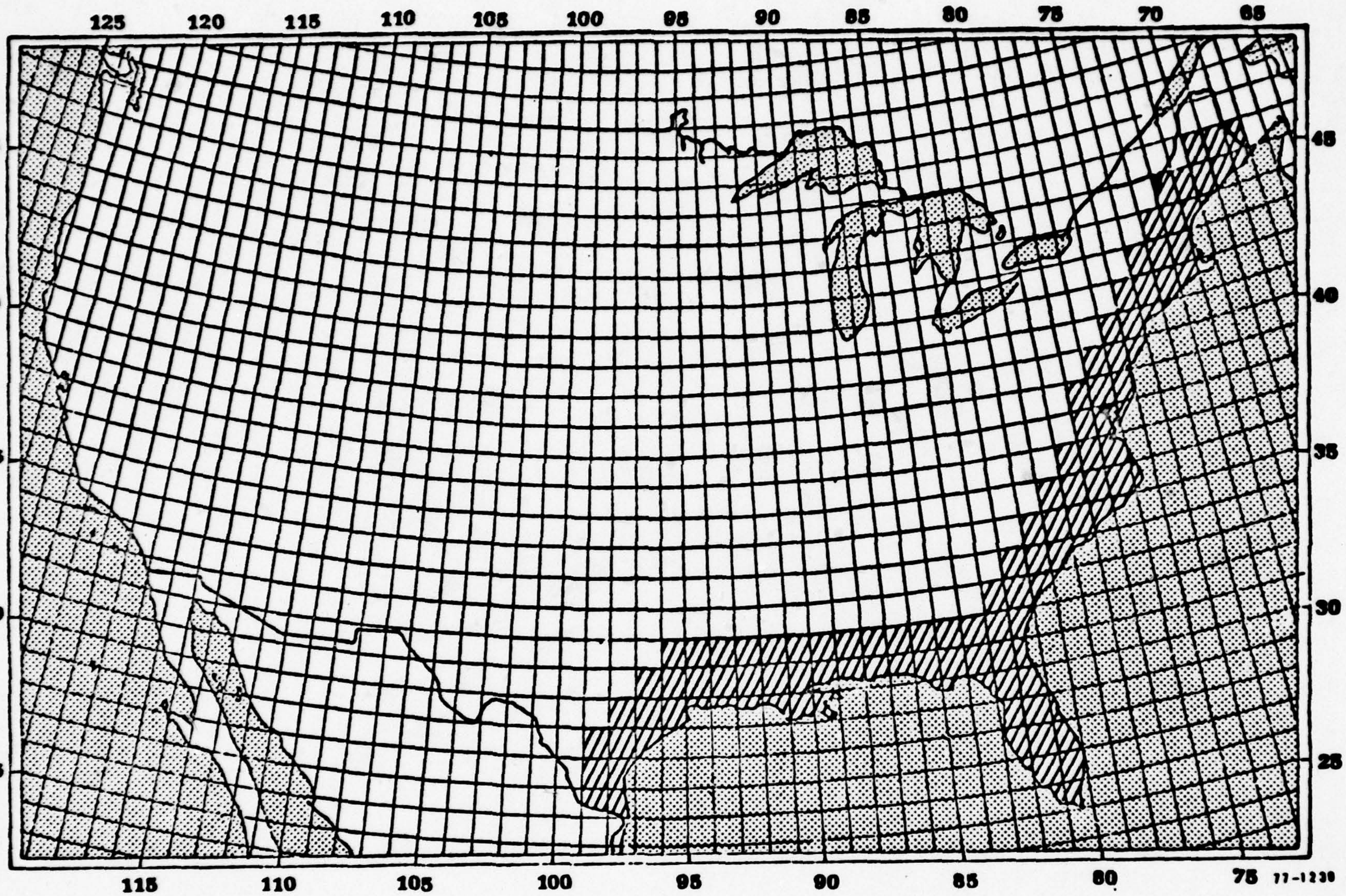

Figure 3-17. 1° by 1° Grid Cells where Hurricane Winds Occur [3-20]

The hurricane wind hazard model is obtained as follows:

- From Figures 3-15 and 3-16, determine the 10 and 50 year return-period winds (at 30 feet, only for sites within the grid elements identified in Figure 3-17).

- Solve for γ and σ using Equation 3-17.

$$\frac{1}{10} = e^{-[V_{10}/\sigma]^{-\gamma}}$$

$$\frac{1}{50} = e^{-[V_{50}/\sigma]^{-\gamma}}$$

solving for γ and σ

$$\gamma = -\ln(\ln 10/\ln 50)/\ln(V_{10}/V_{50})$$

$$\sigma = V_{10}[1/\ln 10]^{-1/\gamma}$$

- Select the proper wind exposure (A,B, or C) for the building under consideration.

- Convert the approporate 50 foot equivalent open country wind velocities from Table 3-7 to 30 foot winds using equation 3-4.

$$V_{30} = \left(\frac{30}{50}\right)^{1/2} V_{50}$$

This is necessary because the Figure 3-15, 3-16 data is for 30 feet instead of 50 feet.

- Obtain the probability of exceeding each open country wind speed limit using equation 3-17.

$$F\left(V > V_{m_{30}}\right) = e^{-\left[\left(V_m/\delta\right)^{-\gamma}\right]}$$

- Obtain the probability of occurrence associated with each wind state. The strike rate for each state, λ_{i3}, is equal to this probability.

$$\lambda_{i3} \doteq P_{i3} = F(V > V_{Li}) - F(V > V_{Ui}) \quad (3\text{-}18)$$

where

V_{Li} = lower windspeed limit of wind state i at 30 feet

V_{Ui} = upper windspeed limit of wind state i at 30 feet

130

3.3 Damage Algorithms

3.3.1 Damage Matrices

The expected economic loss from the occurrence of one of the wind hazards is a function of many variables. These variables include such things as

- the type of construction,
- the quality of the construction,
- the wind loads used to design the structure,
- the proximity of other structures, and
- the terrain roughness.

The problems involved in quantifying this damage are very similar to those previously discussed for fire. For this reason, an approach similar to that adopted for fire was used for wind; a Bayesian probabilistic approach. As before, the method of analysis was to

- Formulate the probabilistic damage model.
- Establish the significant parameters that can be determined explicitly.
- Quantify the probabilistic model using subjective probabilities.
- Analyze the results.

Just as before, we formulate the probabilistic damage model as damage probability matrices (DPM). Although the damage matrix concept has not, to our knowledge, been previously applied to the wind hazard, it seems to be appropriate for use here. Figure 3-18 shows the DPM's that have been developed for ten different structural categories. Two separate damage matrices (Figure 3-19) have also been developed for window damage. The level of damage is described by a series of damage states.

Associated with each damage state and each wind intensity is the probability that that damage state will occur if the building is exposed to that particular wind intensity. Separate DPM's were developed for each of the following structural categories:

- One to three story wood frame residential structures (A).*
- One to three story concrete or masonry wall residential structures (B).
- One to three story wood frame commercial and industrial structures (C).
- One to three story concrete or masonry wall commercial and industrial structures (D).
- One to three story metal (non-steel) commercial and industrial structures (E).
- Four or more story concrete or masonry structures without shear wall or ductile frame (F).
- Four or more story concrete structures with shear wall or ductile frame (G).
- Steel structures with ductile frame, regardless of height (H).
- Mobile homes without engineered tiedowns.
- Mobile homes with engineered tiedowns.

Our attempt was to develop a list of structural categories which was specific and yet at the same time consistent with the complexity of the problem. In addition, two separate damage matrices for window damage were developed:

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*Letters in parentheses refer to code letters used in Figure 3-22.

- Windows in one to three story structures.
- Windows in four or more story structures.

The DPM's were quantified with the use of a survey of selected wind experts in conjunction with another wind hazard study [3-20]. Nineteen wind damage experts, engineers with special expertise in the field of wind effects on buildings, were surveyed. Twelve of them chose to participate. Each participant was asked to fill out a damage matrix (Figure 3-18) for each of the different structure types* assuming a 1976 design code. They were also asked to fill out two damage matrices for window damage (Figure 3-19). In addition, they were asked to estimate the potential change in damage level associated with an increase in design wind load to 1.5 and 3.0 times the 1976 UBC design levels.

The flow chart shown for the fire damage survey (Figure 2-3) also summarizes the survey plan. In practice, only one mailing was made, and the participants were not able to update their initial estimates. The details of the development of these DPM's are provided in Reference 3-20 and Appendix B. The structural DPM's resulting from this survey are presented in Figure 3-18. The window damage matrices are shown in Figure 3-19.

Damage to contents was estimated using the earthquake relationship which relates contents damage to structure damage. A discussion of this procedure is given in Section 4.3.3.

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*The initial survey covered some additional structure types, but it was found that insufficient information was available to distinguish these additional categories.

Figure 3-18. Structural Damage Matrices for Wind

These damage matrices are for buildings designed to the 1976 UBC minimum wind pressure loads corresponding to wind-pressure-map area 30. A copy of the 1976 wind pressure map is shown in Figure 3-20. For buildings desinged to a different wind pressure loading, the central damage ratio is adjusted according to Figure 3-21. Definitions and central damage ratios are provided at the end of this figure.

a. One-Thr[illegible] Story, Wood Frame, Residential

DAMAGE STATE	PERCENT DAMAGE	WIND STATE							
		1	2	3	4	5	6	7	8
None	0 - 0.05%	.926	.669	.356	.197	.113	.089	.064	0
Light	.05- 1.25%	.063	.269	.266	.148	.063	.028	.039	0
Moderate	1.25- 7.5%	.008	.049	.224	.239	.106	.049	.014	.013
Heavy	7.5 - 65%	.001	.010	.130	.239	.314	.086	.021	.013
Very Severe	65 - 100%	.001	.003	.016	.155	.255	.407	.119	.078
Collapse	100%	.001	.001	.008	.021	.150	.340	.744	.898

b. One-Three Story, Concrete or Masonry Wall, Residential

DAMAGE STATE	PERCENT DAMAGE	WIND STATE							
		1	2	3	4	5	6	7	8
None	0 - 0.05%	.959	.772	.442	.339	.152	.103	.066	0
Light	.05- 1.25%	.032	.191	.177	.128	.106	.028	.020	.011
Moderate	1.25- 7.5%	.006	.028	.320	.111	.136	.113	.028	.022
Heavy	7.5 - 65%	.001	.004	.050	.261	.219	.211	.128	.133
Very Severe	65 - 100%	.001	.002	.009	.142	.281	.234	.267	.187
Collapse	100%	.001	.002	.002	.019	.107	.310	.472	.647

c. One-Three Story, Wood Frame, Commercial and Industrial

DAMAGE STATE	PERCENT DAMAGE	WIND STATE							
		1	2	3	4	5	6	7	8
None	0 - 0.05%	.959	.844	.367	.217	.132	.083	.059	.001
Light	.05- 1.25%	.032	.116	.333	.170	.082	.039	.020	.012
Moderate	1.25- 7.5%	.006	.033	.202	.297	.181	.117	.025	.023
Heavy	7.5 - 65%	.001	.003	.064	.164	.379	.117	.057	.063
Very Severe	65 - 100%	.001	.002	.020	.122	.104	.422	.299	.250
Collapse	100%	.001	.001	.013	.030	.121	.222	.540	.650

d. One-Three Story, Concrete or Masonry Wall, Commercial and Industrial

DAMAGE STATE	PERCENT DAMAGE	WIND STATE							
		1	2	3	4	5	6	7	8
None	0 - 0.05%	.967	.903	.567	.440	.191	.103	.071	0
Light	.05- 1.25%	.028	.080	.183	.141	.156	.062	.027	.013
Moderate	1.25- 7.5%	.002	.011	.178	.178	.164	.152	.044	.026
Heavy	7.5 - 65%	.002	.003	.048	.097	.275	.242	.159	.144
Very Severe	65 - 100%	.001	.001	.012	.120	.104	.237	.258	.100
Collapse	100%	0	.001	.012	.024	.109	.203	.440	.717

e. One-Three Story, Metal, (non-steel) Commercial and Industrial

DAMAGE STATE	PERCENT DAMAGE	WIND STATE							
		1	2	3	4	5	6	7	8
None	0 - 0.05%	.956	.894	.494	.359	.174	.117	.067	.002
Light	.05- 1.25%	.041	.083	.300	.169	.119	.063	.056	.014
Moderate	1.25- 7.5%	.001	.020	.136	.247	.146	.089	.061	.028
Heavy	7.5 - 65%	.001	.001	.047	.161	.411	.209	.151	.156
Very Severe	65 - 100%	.001	.001	.012	.052	.114	.364	.229	.097
Collapse	100%	0	0	.011	.012	.036	.158	.436	.703

f. Steel Structure (regardless of height)

DAMAGE STATE	PERCENT DAMAGE	WIND STATE							
		1	2	3	4	5	6	7	8
None	0 - 0.05%	.994	.950	.811	.439	.239	.151	.089	.006
Light	.05- 1.25%	.006	.048	.169	.356	.224	.084	.078	.039
Moderate	1.25- 7.5%	0	.002	.019	.188	.344	.291	.156	.172
Heavy	7.5 - 65%	0	0	.001	.018	.180	.280	.261	.211
Very Severe	65 - 100%	0	0	0	0	.012	.132	.198	.247
Collapse	100%	0	0	0	0	0	.063	.219	.326

g. Four or More Story, Concrete or Masonry, without Shear Wall or Ductile Frame

DAMAGE STATE	PERCENT DAMAGE	WIND STATE							
		1	2	3	4	5	6	7	8
None	0 - 0.05%	.969	.870	.540	.345	.150	.090	.050	.001
Light	.05- 1.25%	.026	.105	.363	.230	.145	.060	.055	.022
Moderate	1.25- 7.5%	.002	.015	.081	.315	.230	.162	.150	.105
Heavy	7.5 - 65%	.002	.008	.013	.075	.365	.225	.177	.108
Very Severe	65 - 100%	.001	.001	.002	.028	.085	.323	.148	.184
Collapse	100%	0	.001	.001	.007	.025	.140	.420	.580

h. Four or More Story, Concrete or Masonry, with Shear Wall or Ductile Frame

DAMAGE STATE	PERCENT DAMAGE	WIND STATE							
		1	2	3	4	5	6	7	8
None	0 - 0.05%	.990	.934	.656	.428	.219	.144	.078	.006
Light	.05- 1.25%	.009	.062	.289	.308	.225	.100	.072	.044
Moderate	1.25- 7.5%	.001	.002	.054	.231	.343	.289	.167	.161
Heavy	7.5 - 65%	0	.001	.001	.031	.197	.256	.244	.189
Very Severe	65 - 100%	0	0	0	.002	.015	.141	.211	.219
Collapse	100%	0	0	0	0	.002	.070	.228	.381

i. Mobile Homes, With Engineered Tiedowns

DAMAGE STATE	PERCENT DAMAGE	WIND STATE							
		1	2	3	4	5	6	7	8
None	0 - 0.05%	.800	.583	.106	.039	.017	.003	.003	.001
Light	.05- 1.25%	.190	.202	.339	.184	.111	.071	.035	.001
Moderate	1.25- 7.5%	.006	.167	.278	.251	.061	.049	.056	.029
Heavy	7.5 - 65%	.001	.032	.150	.235	.194	.064	.069	.056
Very Severe	65 - 100%	.001	.009	.092	.154	.233	.167	.056	.048
Collapse	100%	.001	.007	.036	.136	.383	.647	.781	.865

j. Mobile Homes, Without Engineered Tiedowns

DAMAGE STATE	PERCENT DAMAGE	WIND STATE							
		1	2	3	4	5	6	7	8
None	0 - 0.05%	.506	.267	.039	.017	.009	.002	.001	0
Light	.05- 1.25%	.339	.328	.158	.133	.069	.020	.001	0
Moderate	1.25- 7.5%	.104	.222	.087	.067	.056	.072	.046	0
Heavy	7.5 - 65%	.048	.107	.178	.094	.072	.056	.047	.001
Very Severe	65 - 100%	.002	.064	.267	.191	.122	.061	.033	.017
Collapse	100%	.001	.012	.272	.498	.672	.789	.872	.982

k. Definitions/Central Damage Ratios

DAMAGE STATE	DAMAGE RANGE	CENTRAL DAMAGE RATIO	DESCRIPTION
None	0 - 0.05%	0	No damage.
Light	.05 - 1.25%	.0025	Minor ceiling tile or partition cracking; possible damage due to missiles.
Moderate	1.25 - 7.5%	.031	Many partitions cracked or ceiling tiles fallen down, a few structural members appear to be stressed beyond yield level.
Heavy	7.5 - 65%	.221	Significant number of structural members with structural damage, or damage to a structural system; roof having major damage or blown off.
Very Severe	65 - 100%	.806	Major damage; structure standing but will probably be taken down; no structural system collapsed.
Collapse	100%	1.000	Structure does not remain standing.

DAMAGE STATE	WIND STATE							
	1	2	3	4	5	6	7	8
One-Three Story, Wood Frame, Residential								
None	.065	.381	.881	1.394	2.328	2.563	2.587	0.
Light	1.455	.882	.862	.888	1.039	2.277	2.550	0.
Moderate	2.646	.861	.931	.885	.723	1.500	2.383	2.646
Heavy	2.646	1.803	1.701	1.072	.711	.845	1.319	2.646
Very Heavy	2.646	2.646	2.040	1.472	.795	.783	.840	1.347
Collapse	2.646	2.646	2.186	2.311	1.675	.941	.403	.181
One-Three Story, Concrete or Masonry Wall, Residential								
None	.062	.313	.861	1.040	1.944	2.727	2.747	0.
Light	1.122	1.184	.623	.827	1.250	1.161	2.345	2.828
Moderate	2.828	1.233	.968	.787	1.030	1.194	1.233	2.828
Heavy	2.828	2.828	.816	1.190	.828	1.175	1.900	1.904
Very Heavy	2.828	2.828	1.945	1.536	1.100	1.236	1.296	1.626
Collapse	2.828	2.828	2.828	2.476	2.015	1.221	.899	.629
One-Three Story, Wood Frame, Commercial and Industrial								
None	.051	.120	.862	1.328	2.069	2.623	2.708	2.828
Light	1.022	.608	.812	.932	1.296	1.457	2.345	2.552
Moderate	2.828	1.225	1.029	.815	1.029	1.616	1.495	2.680
Heavy	2.828	2.828	1.426	1.049	.816	.926	1.158	1.638
Very Heavy	2.828	2.828	1.650	1.834	.878	.828	1.101	1.337
Collapse	2.828	2.828	2.345	1.750	2.024	1.359	.751	.609
One-Three Story, Concrete or Masonry Wall, Commercial and Industrial								
None	.041	.073	..700	.768	1.532	2.347	2.593	0.
Light	1.161	.556	1.128	.723	1.011	1.308	2.263	2.345
Moderate	2.828	1.871	1.230	1.300	.784	.902	1.118	2.441
Heavy	2.828	2.828	1.978	1.537	.965	.941	1.461	1.738
Very Heavy	2.828	2.828	2.552	2.010	1.162	1.047	.954	1.080
Collapse	0.	2.828	2.552	1.671	2.139	1.457	.795	.472
One-Three Story, Metal, Commercial and Industrial								
None	.051	.097	.713	.944	1.802	2.080	2.345	2.828
Light	1.194	.693	.857	.748	.944	1.410	1.871	2.192
Moderate	2.828	1.650	.904	.896	.824	1.209	1.206	2.263
Heavy	2.828	2.828	1.967	1.177	.638	.986	1.678	1.628
Very Heavy	2.828	2.828	2.552	1.787	.864	.857	1.046	1.163
Collapse	0.	0.	2.828	2.552	1.729	1.216	.904	.499

Figure 3-18ℓ. Coefficients of Variations

DAMAGE STATE	WIND STATE							
	1	2	3	4	5	6	7	8
Four or More Story Structures-Ductile Steel Frame								
None	.011	.036	.234	.776	1.422	1.886	1.945	2.828
Light	1.918	.737	1.027	.769	.690	.980	1.425	2.080
Moderate	0.	2.828	1.737	.959	.679	.706	1.108	1.263
Heavy	0.	0.	2.828	1.852	1.147	.812	.765	.856
Very Heavy	0.	0.	0.	0.	2.552	1.435	1.132	1.045
Collapse	0.	0.	0.	0.	0.	2.500	1.598	1.200
Four or More Story, Concrete or Masonry, without Shear Wall or Ductile Frame								
None	.041	.139	.649	.861	1.844	2.354	2.683	3.000
Light	1.266	.751	.764	.569	.865	1.384	1.839	2.711
Moderate	3.000	2.134	.893	.670	.525	1.066	1.466	1.893
Heavy	3.000	2.077	2.334	1.125	.715	.990	1.467	1.233
Very Heavy	3.000	3.000	2.000	2.130	1.317	.909	1.090	1.372
Collapse	0.	3.000	3.000	2.218	1.844	1.204	.891	.717
Four or More Story, Concrete or Masonry, with Shear Wall on Ductile Frame								
None	.017	.038	.447	.797	1.443	1.828	2.080	2.828
Light	1.630	.545	.859	.684	.637	.943	1.427	2.151
Moderate	2.828	2.828	1.184	.722	.609	.641	1.039	1.257
Heavy	0.	2.828	2.828	1.299	1.046	.687	.792	.957
Very Heavy	0.	0.	0.	2.828	2.192	1.306	1.052	1.035
Collapse	0.	0.	0.	0.	2.828	2.192	1.528	1.044
Mobile Homes, with Engineered Tiedowns								
None	.508	.475	1.874	2.407	2.828	2.828	2.828	2.828
Light	1.582	.652	.945	1.494	2.263	2.552	2.080	2.828
Moderate	2.828	1.208	.745	.909	1.379	1.987	2.211	2.441
Heavy	2.828	1.929	1.197	.802	1.134	1.497	1.958	2.494
Very Heavy	2.828	1.945	1.397	.972	1.147	1.464	1.333	1.526
Collapse	2.828	2.345	2.635	1.799	1.005	.766	.594	.475
Mobile Homes, without Engineered Tiedowns								
None	.686	.906	2.407	2.828	2.828	2.828	2.828	0.
Light	.912	.772	1.788	1.869	2.278	1.886	2.828	0.
Moderate	1.400	.973	1.309	1.581	1.918	2.041	2.752	0.
Heavy	2.614	1.729	1.110	1.128	1.464	1.918	2.680	2.828
Very Heavy	2.828	1.977	.914	1.104	.907	1.076	1.581	1.918
Collapse	2.828	2.552	1.061	.803	.551	.425	.321	.034

Figure 3-18ℓ. Coefficients of Variations (Continued)

DAMAGE MATRICES

DAMAGE STATE	PERCENT DAMAGE	WIND STATE 1	2	3	4	5	6	7	8
One-Three Story Structures									
None	0 - 0.05%	.939	.810	.367	.222	.167	.131	.082	.038
Light	.05- 1.25%	.056	.151	.383	.111	.061	.056	.025	.040
Moderate	1.25- 7.5%	.006	.026	.172	.328	.072	.056	.038	.048
Heavy	7.5 - 65%	0	.013	.053	.178	.344	.100	.092	.050
Very Severe	65 - 100%	0	0	.024	.161	.356	.656	.764	.825
Four or More Story Structures									
None	0 - 0.05%	.922	.821	.439	.244	.148	.111	.079	.022
Light	.05- 1.25%	.067	.123	.383	.228	.131	.061	.060	.046
Moderate	1.25- 7.5%	.009	.033	.106	.267	.273	.178	.100	.116
Heavy	7.5 - 65%	.001	.020	.044	.128	.210	.239	.089	.081
Very Severe	65 - 100%	.001	.002	.028	.133	.239	.411	.672	.736

COEFFICIENTS OF VARIATION

DAMAGE STATE	WIND STATE 1	2	3	4	5	6	7	8
One-Three Story Structures								
None	.081	.179	.925	1.485	1.811	2.176	2.593	2.828
Light	1.215	.632	.657	1.012	1.206	1.491	2.151	2.635
Moderate	2.828	1.979	.598	1.040	1.269	1.333	1.581	2.238
Heavy	0	2.345	1.215	1.172	.978	1.266	1.244	1.447
Very Severe	0	0	2.552	1.476	1.102	.694	.584	.548
Four or More Story Structures								
None	.105	.200	.750	1.210	1.927	2.223	2.368	2.828
Light	1.212	.679	.730	.915	.943	1.076	1.352	2.088
Moderate	2.828	2.000	.755	1.027	1.093	1.011	1.491	1.686
Heavy	2.828	2.345	1.794	1.430	1.114	1.048	.786	1.138
Very Severe	2.828	2.828	2.263	1.768	1.460	1.027	.535	.480

Figure 3-19. Window Damage

Definitions for Window Damage

DAMAGE STATE	DAMAGE RANGE	CENTRAL DAMAGE RATIO	DESCRIPTION
None	0 - .05%	0	No damage.
Light	.05 - 1.25%	.0025	Some windows lost, mainly at corners.
Moderate	1.25 - 7.5%	.031	Many windows lost.
Heavy	7.5 - 65%	.221	Most windows lost.
Very Severe	65 - 100%	1.000	Essentially all windows lost.

3.3.2 Damage Reduction Factor

The damage matrices shown in Figures 3-18 and 3-19 are applicable to only one design level, that corresponding to the minimum design wind pressure load specified by the 1976 UBC for wind-pressure-map area 30. However, in the parts of the country, in other years, or under other than minimum specifications, buildings have been and will be designed and built to different wind pressure loadings. To account for this variability in design loads, a damage reduction factor has been defined using information obtained form the questionnaire.

The survey respondants were asked to estimate the potential change in damage associated with an increase in the design wind loads to 1.5 and 3.0 times the UBC minimum requirements. Results

DESIGN WIND LOAD	DAMAGE REDUCTION FACTOR FROM SURVEY (MEAN VALUE)
1.5 UBC	0.64 (σ = 0.26)
3.0 UBC	0.41 (σ = 0.33)

were obtained for both structural and window damage. these estimates, combined with the requirement that 1.0 UBC must have a damage reduction factor of 1.0 and combined with the fact that the smallest map pressure (Figure 3-20) is 20 psf, produce the damage reduction relationship shown in Figure 3-21. This factor, in turn, is used in the loss equation (equation 3-19) to scale the central damage ratio either up or down for the building under consideration. It is applicable for both structural and window damage.

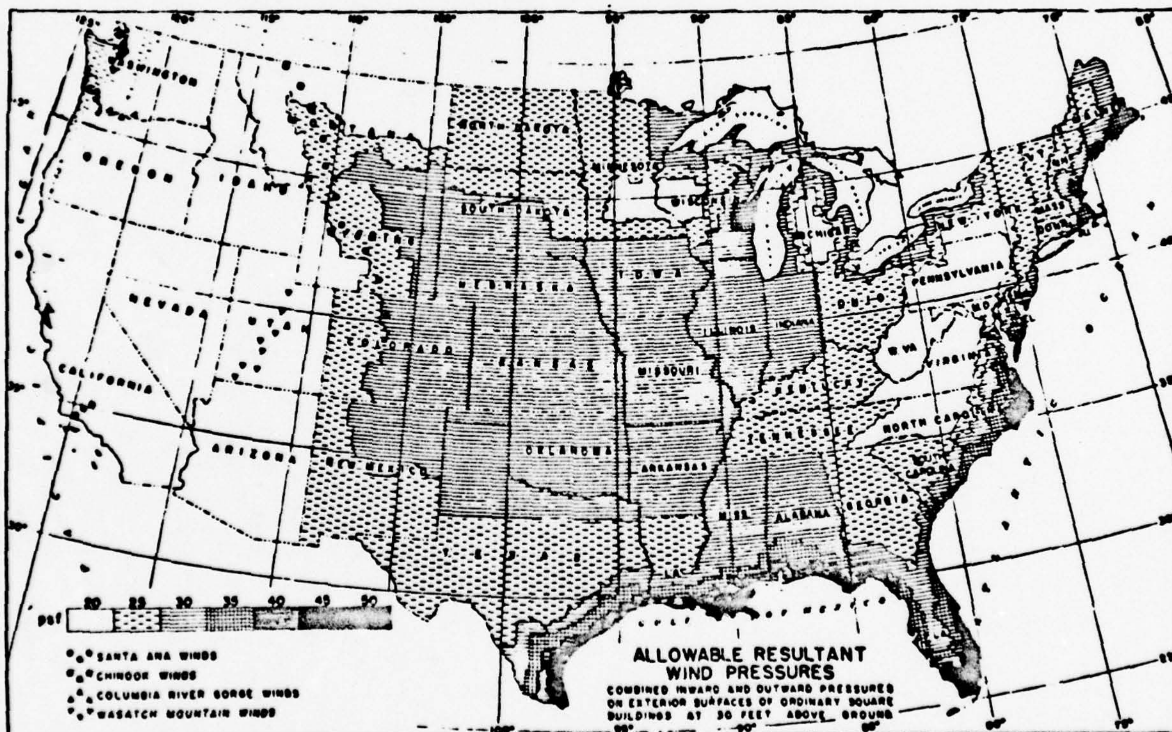

Figure 3-20. 1976 UBC Wind Pressure - Map [3-23]

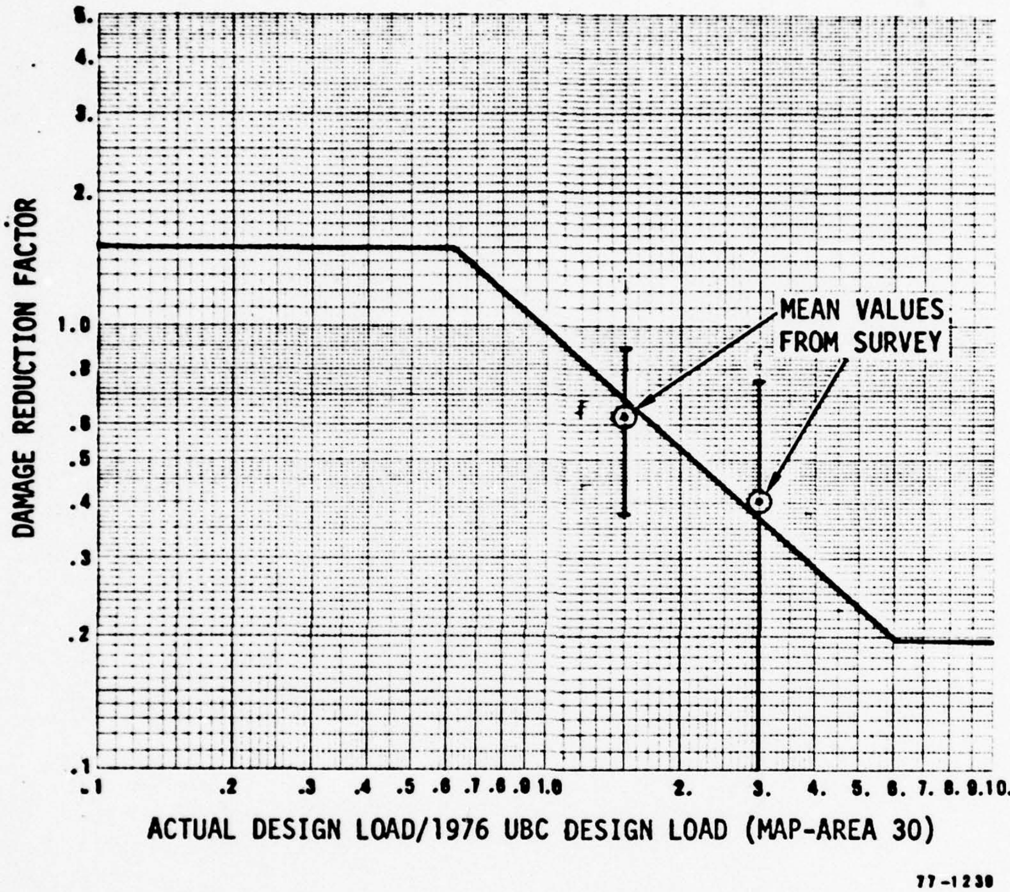

Figure 3-21. Damage Reduction Factor

3.3.3 Wind States

Associated with each damage-wind state is the probability that that damage state will occur if the building is exposed to that particular wind state. The wind ranges for each of the eight wind states are as follows:

WIND RANGE (mph) AT BUILDING SITE	WIND STATE							
	1	2	3	4	5	6	7	8
FOR TORNADO	40 to 72	Not Used	73 to 112	Not Used	113 to 157	158 to 206	207 to 260	261 to 318
FOR SEVERE LOCAL WIND	37.5 to 62.5	62.5 to 87.5	87.5 to 112.5	112.5 to 137.5	137.5 to 175	175 to 225	225 to 275	275 to 325
FOR HURRICANE	Not Used	73.0 to 87.5	87.5 to 112.5	112.5 to 137.5	137.5 to 175	175 to 225	225 to 275	275 to 325

The six wind speed *ranges* used for tornado correspond to the 6 Fujita Ratings, F0 to F5. Although these ranges are not the same as for the other two hazards, the damage matrices are not sufficiently precise to distinguish the difference.

These velocity ranges for severe local wind and hurricane must not be used directly in the probability-of-occurrence calculations. They must first be converted to an equivalent open country velocity using Table 3-7.

3.4 Expected Loss

3.4.1 Economic and Mission Losses

Section 3.2 discussed the procedure used to obtain the probability of a site, or structure, being struck by each of the wind hazard intensities. The relationship between the occurrence of a particular wind speed and its induced damage was then quantified using the wind probability matrices (Section 3-3).

The procedure* followed to calculate the expected annual average economic loss is:

- Determine the probability of the site being struck by each intensity level of the wind hazard being considered (i.e., the hazard model).
- Determine the corresponding damage state probabilities (i.e., the damage algorithm).
- Obtain the total replacement value of the structure and its contents (i.e., the exposure model).
- Determine the expected average annual loss using:

$$E(LOSS) = \sum_{g=1}^{3} \sum_{h=1}^{3} V_h \sum_{i=1}^{N(g)} \lambda_{ig} \sum_{j=1}^{M(h)} D_{jh} Q_{ijh} \qquad (3\text{-}19)$$

where g = index for type of wind

1=tornado
2=severe local wind
3=hurricane

*Figure 3-1 describes this procedure schematically.

h = index for type of damage

1 = structure damage
2 = window damage
3 = contents damage

i = index for intensity levels

$N(g)$ = number of intensity levels

$N = 6$ tornado ($g = 1$)
$N = 8$ severe wind ($g = 2$)
$N = 7$ hurricane ($g = 3$)

j = index for damage

$M(h)$ = number of damage states

$M = 6$ structure damage ($h = 1$)
$M = 5$ window damage ($h = 2$)
$M = 6$ contents damage ($h = 3$)

λ_{ig} = strike rate (Hazard Model)

for tornado use equation 3-1

for severe wind use equation 3-12

for hurricane use equation 3-18

Q_{ijh} = Probability of damage state j given occurrence of wind intensity i

D_{jh} = damage ratio = central damage ratio times damage reduction factor

maximum value = 1.0

Structural damage

see Figure 3-16 for central damage ratio

see Figure 3-21 for damage reduction factor

Window damage

see Figure 3-19 for central damage ratio

see Figure 3-21 for damage reduction factor

Content damage

same as for earthquake (equation 4-10)

V_h = value exposed (Exposure Model)

The determination of mission reliability (see Section 6.1) requires knowledge of the reliability of each structure in the mission network. The building reliability (i.e., the probability that the building will remain functional throughout the year) is calculated using equation 3-20. Implicit in the formulation is the determination that 20 percent damage to the structure will cause the structure to be vacated. This is the same cutoff used for earthquake and is based on the same arguments (see Section 4.4.2).

$$\begin{aligned} \text{RELIABILITY} &= 1 - \text{Probability (failure)} \\ &= 1 - \Pi_{i=1}^{3}(1 - P_i) \\ &= 1 - (P_1 + P_2 + P_3 - P_1P_2 - P_1P_3 \\ &\quad - P_2P_3 + P_1P_2P_3) \end{aligned} \tag{3-20}$$

where

P_1 = Probability (failure due to tornado)

$$= \sum_{i=1}^{N(1)} P_{i1} \sum_{j=4}^{6} Q_{ij1}$$

P_2 = Probability (failure due to severe local wind)

$$= \sum_{i=1}^{N(2)} P_{i2} \sum_{j=4}^{6} Q_{ij1}$$

P_3 = Probability (failure due to hurricane)

$$= \sum_{i=1}^{N(3)} P_{i3} \sum_{j=4}^{6} Q_{ij1}$$

P_{i1} = Probability of occurrence of tornadoes of intensity i given by equation 3-1.

P_{i2} = Probability of occurrence of severe local winds of intensity i given by equation 3-13.

P_{i3} = Probability of occurrence of hurricane wind of intensity i given by equation 3-18.

The three wind hazards are assumed to be mutually exclusive.

3.4.2. Personnel Losses

Similar to the problem for other hazards, the quantification of death and injury from tornadoes and windstorms to occupants of buildings is a difficult problem. There does not appear to be any work which has been done to provide a damage-state/casualty-rate relationship for wind. In light of this paucity of data, the only option open is to use the relationships proposed for earthquake. Since the damage states used in the wind damage algorithms are identical to those used for the earthquake relations, the application of the above rates to the wind hazard would follow the same line described for earthquake. The details of the procedure are discussed in Section 4.4.3.

Our recommendation, with respect to earthquake, is that the mitigation methodology not include consideration of expected casualties. Since the application of the earthquake rates to windstorm introduces even more uncertainty, this recommendation is even more applicable for windstorm. The present state of the art of wind research does not warrant the use of wind casualty rates for decisions at the building level.

From 1953 through 1970 there were 2087 deaths in the United States from tornadoes and 2671 deaths from windstorms[3-17]. Since the average population of the United States during this period was about 178 million[3-18] the death rate was about 0.2×10^{-9} (*assuming everyone was exposed* the entire year). This is the level people have historically accepted for involuntary risk (see Section 1.2). Consequently even the necessity to develop a mitigation methodology based on casualty rates seems unfounded. Certainly this rate is higher in those areas, such as Oklahoma, which have the higher incidences of tornadoes, but this should not affect the basic conclusion stated above.

3.5 Methodology

The methodology for wind, as for fire, requires the initial input of specific data. The different data categories consist of hazard and damage, exposure and vulnerability, and mitigation and cost. A listing of each category, as well as the elements that comprise them, is provided in Section 3.1.

To begin the analysis, the structure identification number must be given. In addition, it is necessary to specify the type of wind to which the structure is vulnerable; whether it be hurricane, tornado, and/or local wind. This information is also treated as in-line input as shown in Figure 3-22. Additional data, shown being received from the side, is comprised of that which is used by all structures. Basically, this data includes probability/intensity relationships and intensity/damage matrices for hurricane, tornado, and local wind. In addition, cost factors for modifying the structural and non-structural systems to 1, 2, and 3 times the basic UBC wind load and unit costs for anchoring are given. These cost factors represent those used in assessing the cost for existing structures. The next step involves classifying the structure type. The different types being considered are listed in Table 3-1 with letters that correspond to those on Figure 3-22.

Each of these categories has separate damage matrices associated with it. They can be combined, however when considering mitigation alternatives. Types A and C are combined into one class labeled as "wood"; types B, D, F and G are combined under "reinforced concrete"; and Types E and H are combined

STRUCTURE TYPES

- A 1 TO 3 STORY, WOOD FRAME, RESIDENTIAL
- B 1 TO 3 STORY, CONCRETE OR MASONRY, RESIDENTIAL
- C 1 TO 3 STORY, WOOD FRAME, COMM/IND
- D 1 TO 3 STORY, CONCRETE OR MASONRY, COMM/IND
- E 1 TO 3 STORY, METAL, COMM/IND
- F 4 OR MORE STORY, CONCRETE OR MASONRY STRUCTURES, NO SHEAR WALL OR DUCTILE FRAME
- G 4 OR MORE STORY, CONCRETE OR MASONRY STRUCTURES, WITH SHEAR WALL OR DUCTILE FRAME
- H STEEL STRUCTURES, WITH DUCTILE FRAME, REGARDLESS OF HEIGHT

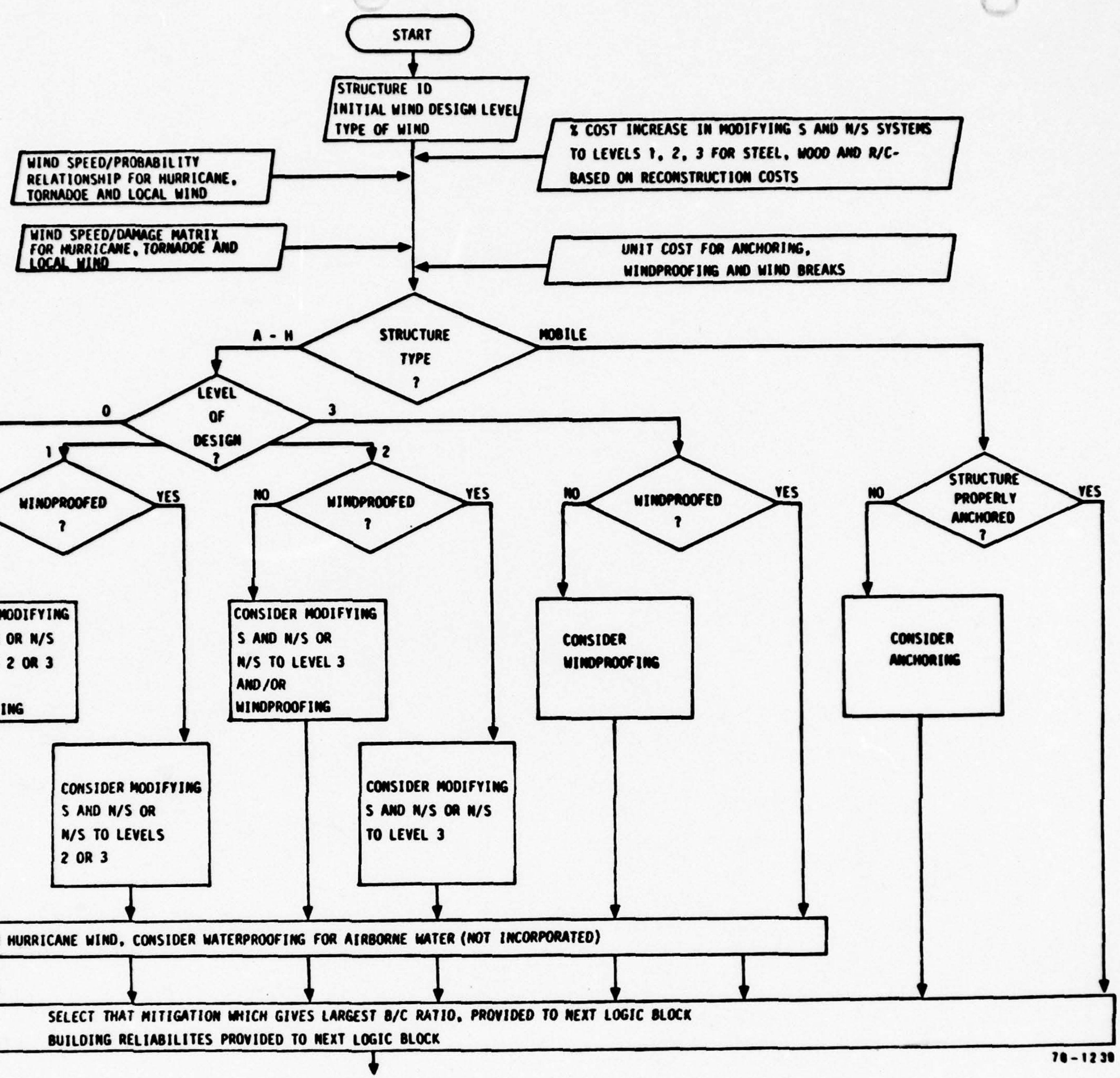

Figure 3-22. Wind Hazard

under "steel." Mobile homes remain separate. The reason for combining these categories stems from the fact that mitigations and cost factors are the same within each group.

Once the structure type has been established, the methodology branches one of two ways: construction types A-H or mobile homes. If the structure falls in the first category, we must first determine the building's current level of design. This information is available from the Base Inspection form (Section 7). Here four levels are defined: minimum wind protection, 0; one times UBC wind loads, 1; two times UBC wind loads, 2; and three times UBC wind loads, 3. Once this is determined,the appropriate branch is followed and whether or not the structure has been windproofed is tested. If it has, modifying the structural and non-structural systems to higher levels of design is considered.

The modification of the non-structural system is considered as a separate mitigation, while the structural modification includes all non-structural changes. The reason for this is that the cost of non-structural changes is small compared to that for structural changes. Therefore, it is economically sensible to consider both as one mitigation. If windproofing was not part of the original construction, it is also considered. If the subject structure is a mobile home, proper anchoring is considered.

In considering the different mitigations, all relevant wind hazards must be considered. That is, if a particular facility is vulnerable to all three types of wind, the expected reduction in damage due to a mitigation must be calculated for

all three wind types. The reductions in damage for each are then aggregated and the total divided by the cost of the mitigation to obtain the benefit/cost ratio. The reductions in damage are calculated by subtracting the expected damage after implementing the mitigation from the initial expected damage. The expected damages are calculated using Equations 3-21 and 3-22 as applicable.

Once the benefit/cost ratios are calculated for all mitigations, the best mitigation is selcted and sent to the next logic block. In addition, original building reliabilities are provided.

3.6 Availability and Adequacy of Data

Although the approach followed here for severe wind is not based on the extreme annual wind characterizations developed by Thom[3-1], some recent work by Simiv and Filliben[3-9] on extreme annual wind characterizations raises some interesting questions about the wind data.

Thom chose a Fisher-Tippit Type II probability distribution to describe severe wind. However, another common extreme value distribution function has been utilized, often called a Type I distribution

$$F_I(V) = \exp\{-\exp[-(V - \mu)/\sigma]\}$$

It can be shown that $F_{II}(V) \to F_I(V)$ as $\sigma \to \infty$. This latter distribution has been used in developing the wind velocities used in the National Building code of Canada[3-11]. Since the parent population (e.g., largest weekly wind speed) appears to follow a distribution of the exponential type (e.g., a Rayleigh distribution) it has been argued that the largest yearly wind speed should follow a Type I distribution[3-11].

The recent Simiv-Filliben study[3-9] presents many interesting and important points. A statistical analysis of extreme wind data at 21 United States weather stations was performed to address the question of the appropriate type of distribution; i.e., Type I versus Type II, and also to comment on whether a 20-year length of data (i.e., the approximate length of Thom's data) is sufficient for making relaible predictions of extreme wind speeds.

Simiv and Filliben statistically estimated the value of the tail length parameter for a Type I distribution and then compared Type I wind speeds corresponding to 50, 100, and 1000 year return periods with the corresponding wind speeds for Type II distribution model. They concluded that

> No single distribution was universally applicable to all the data sets. The Type I distribution was applicable in about 45% of the cases. In about 25% of the cases, the tail length parameter was $10 \leq \gamma_{opt} \leq 39$, in about 10% of the cases $5 \leq \gamma_{opt} \leq 9$, and in about 20% of the cases $2 \leq \gamma_{opt} \leq 4$.

Furthermore, the following conclusion is important in regions of the U.S. where tropical storms are severe:

> No necessary correlation was noted between type of wind climate and the magnitude of the tail length parameter, i.e., both Type I distributions and Type II distributions with small tail length parameters were found to fit series of data generated by tropical storms, as well as data generated by extra-tropical storms.

This latter conclusion differs from that of Thom in that he found that the value of the tail length parameter, for a Type II distribution, was approximately 9.0 for extratropical storms and 4.5 for tropical storms[3-8]. The authors also conclude that there are significant differences, 15 to 100 percent on the average between 50-year wind speeds obtained using a 20-year record length with those obtained using the 37-year record length.

What then can be concluded in light of the previous comments and the widespread U.S. use of the Thom wind maps? It is

apparent that the statistical analysis of wind speeds over the U.S. should again be performed using the additional years of data since Thom's study and new wind speed maps should be developed. Also, it is clear that within local geographic regions the type of distribution as well as the values of its parameters may significantly differ. In particular, in populous areas a microzonation of wind speeds should be carried out.

As with the other hazards, this brief presentation of controversy in the area of wind is intended to give the reader a feeling for the level of confidence associated with hazard models presently available.

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4. EARTHQUAKE HAZARD

4.1 Introduction

Recent developments in geology have tended to confirm the plate tectonic theory of continental motion. Although many specific questions remain unanswered, the basic idea is as follows. The earth's crust is divided into huge plates afloat on the mantle. When such a plate is in motion, material for it is supplied at one edge and destroyed at the other. Wherever two plates meet, there is an area of high seismic activity. The west coast of the United States is one such area.

The slow constant plate movement produces a buildup of strain in the earth's crust. Eventually, this accumulation of strain and strain energy exceeds the strength of the rocks and a sudden rupture occurs which releases the stored energy. The result is a movement of a portion of the earth's crust and the generation of vibration waves spreading out from the earthquake focus like waves spreading out from a pebble thrown into a pond of water. These actions cause permanent changes in the earth's topography and may cause extensive damage to man and his structures. There are three basic failure mechanisms associated with an earthquake: shaking, breaking, and water related failures.

4.1.1 Shaking

Shaking causes the greatest amount of damage in populous areas. It is estimated that in California more than 95 percent of all the damages that have been caused by earthquakes have resulted from: (1) shaking which damaged the structure directly, (2) shaking which caused soil failure beneath the foundation of the structure, and (3) shaking which caused the soil

beneath the foundation to densify, and settle, thus failing the structure.

4.1.2 Breaking

The physical breaking of the earth's surface results in some of the most spectacular evidence of the energy released by an earthquake. These breaks are caused by one of four different processes: Faulting is the displacement of two portions of the earth relative to one another along the fault plane on which the earthquake originated. Lurching is the cracking and rupturing of soils at places other than directly along faults. This is caused by the inability of large masses of unconsolidated solids to support the shaking accelerations. It is analagous to what happens when you put sand in a cup and shake the cup. Liquefaction occurs when the shaking action causes water saturated soils to turn to quicksand. Slope failures are landslides which result when the shaking accelerations exceed the strength of the rock or soil and the resulting fractures allow the material to slide downhill.

4.1.3 Water Related Failures

Water related failures generally involve the motion of free-standing water resulting from the movement of the earth during an earthquake. Three different processes are involved: a tsunami is a seismic sea wave. It may be generated by a submarine earthquake, landslide, or volcanic eruption. When one is generated, it can propagate for thousands of miles and cause a series of waves to run up as high as 50 to 100 feet on a seashore. Any structure in its path would be severely damaged if not totally destroyed. There can be considerable life lost if people are caught in the path of the tsunami. When applicable, the tsunami hazard is considered as part of the flood hazard.

Seiche results from the shaking of a bay, lake, or pond. Again, the water waves could cause severe damage to structures and death or injury to persons in the path of the water waves. Dam Failure is often important. The water can overtop the dam, the dam can fail by the added force caused by the earthquake shaking, or the dam may fail by liquefaction of the dam materials (if it is an earth-fill dam). The sudden torrent of water could cause severe property damage and life loss due to inundation.

4.1.4 Consideration of Methodology

Historically, it has been shown that ground shaking is the greatest single cause of damage. For example, during approximately 200 years of historical evidence of earthquake in California, only 800 miles of documented fault rupture have occured. And 600 of these have occurred on one single fault system, the San Andreas. The remaining 200 miles of rupture, spread over a period of 200 years, account for approximately one mile of fault break per year somewhere in California (158,693 square miles).

Contrast the above figures with the fact that over 20 percent of the state of California has suffered earthquake intensities over the same 200 years which would have produced about 8 percent damage to any structure in those areas. For this reason only shaking has been included in the methodology presented here.

The salient features of the approach used for the earthquake hazard are summarized in Table 4-1 and discussed in the following subsections. The hazard model is based on work performed at the J. H. Wiggins Company and reported in NBS BSS 61[4-1]. The details are given in Section 4.2. The procedure

Table 4-1. Information Requirements for Earthquake

HAZARD AND DAMAGE	DATA SOURCE
Hazard Model	
Earthquake Probability	BSS61[4-1]
Structural Damage	
Damage Matrices (High-Rise Buildings) ● UBC Design Levels 0,1,2, & 3 ● UBC Design Level S	MIT-CE-R74-15[4-4]
Damage Relations (Low-Rise Buildings) ● Residential, Commercial/Industrial ● Structure Quality	Developed In-House
Content Damage	
Damage Relations ● Content Quality	Developed In-House
Life Loss	
Casualty Rate	MIT-CE-R74-15[4-4] with Qualifications
Mission Reliability	
Damage Level Assigned to Mission Failure	Assigned (Building Non-Functional if Damage Exceeds 20%)

EXPOSURE AND VULNERABILITY	DATA SOURCE
Building	
Structure Age	Class 2 Property Inventory
Type of Construction ● Steel ● Reinforced Concrete ● Ordinary Wood Frame ● Mobile Home	Base Inspection
Design Level (For High-Rise Buildings) ● UBC Design Levels 0,1,2,&3 ● UBC Design Level S	Base Inspection

Table 4-1. Information Requirements for Earthquake (Continued)

EXPOSURE AND VULNERABILITY	DATA SOURCE
Building (Continued)	
Structure Quality (For Low-Rise Bldgs) ● Framing System and Walls ● Diaphragm and Bracing System ● Partitions ● Special Hazards ● Physical Condition	Base Inspection
Is Mobile Structure Properly Anchored ● Yes ● No	Base Inspection
Number of Stories	Property Inventory
Value of Contents ● Class 3 and 4 Property ● Inventory Material ● Minor Property ● Exchange and Commissary Property ● Special Services Property ● Surplus Property ● Clubs, Other	Property Control Offices
Contents Quality	Base Inspection
MITIGATIONS AND COST	**DATA SOURCE**
Cost Data	
Construction Costs ● Replacement Cost for Existing Structure ● Original Cost for Proposed Structure	Property Inventory
Mitigation Cost Factors for Proposed Structure (For High-Rise and Low-Rise Buildings) ● Designing Structural and Non-Structural Systems	
Steel Structure ● UBC Levels 1,2, & 3 ● UBC Level S	Leslie [4-6] SEAOC [4-7]

Table 4-1. Information Requirments for Earthquake (Continued)

MITIGATIONS AND COST	DATA SOURCE
Cost Data (Continued)	
Reinforced Concrete Structure	Same
● UBC Levels 1,2, & 3	
● UBC Level S	
Ordinary Wood Frame	Same
● UBC Levels 1,2, & 3	
● UBC Level S	
Mitigation Cost Factors for Existing Structure (For High-Rise and Low-Rise Buildings)	
● Modifying Structural and Non-Structural Systems	
Steel Structure	Same
● UBC Levels 1,2, & 3	
● UBC Level S	
Reinforced Concrete Structure	Same
● UBC Levels 1,2, & 3	
● UBC Level S	
Ordinary Wood Frame	Same
● UBC Levels 1,2, & 3	
● UBC Level S	
Cost Factor for Anchoring	Telephone Survey

to be followed in calculating the risk is shown schematically in Figure 4-1 even though all of the terms have not yet been defined. This figure may be helpful in following the discussions in Sections 4.2, 4.3, and 4.4 of hazard, damage and risk.

Two approaches were used for the earthquake damage algorithm: one for low rise structures (developed in-house) and one for high rise structures (developed at MIT). These algorithms are discussed in Section 4.3.

The exposure and vulnerability data are similar to those required for fire and wind. The acquisition of this information is discussed in Section 7.

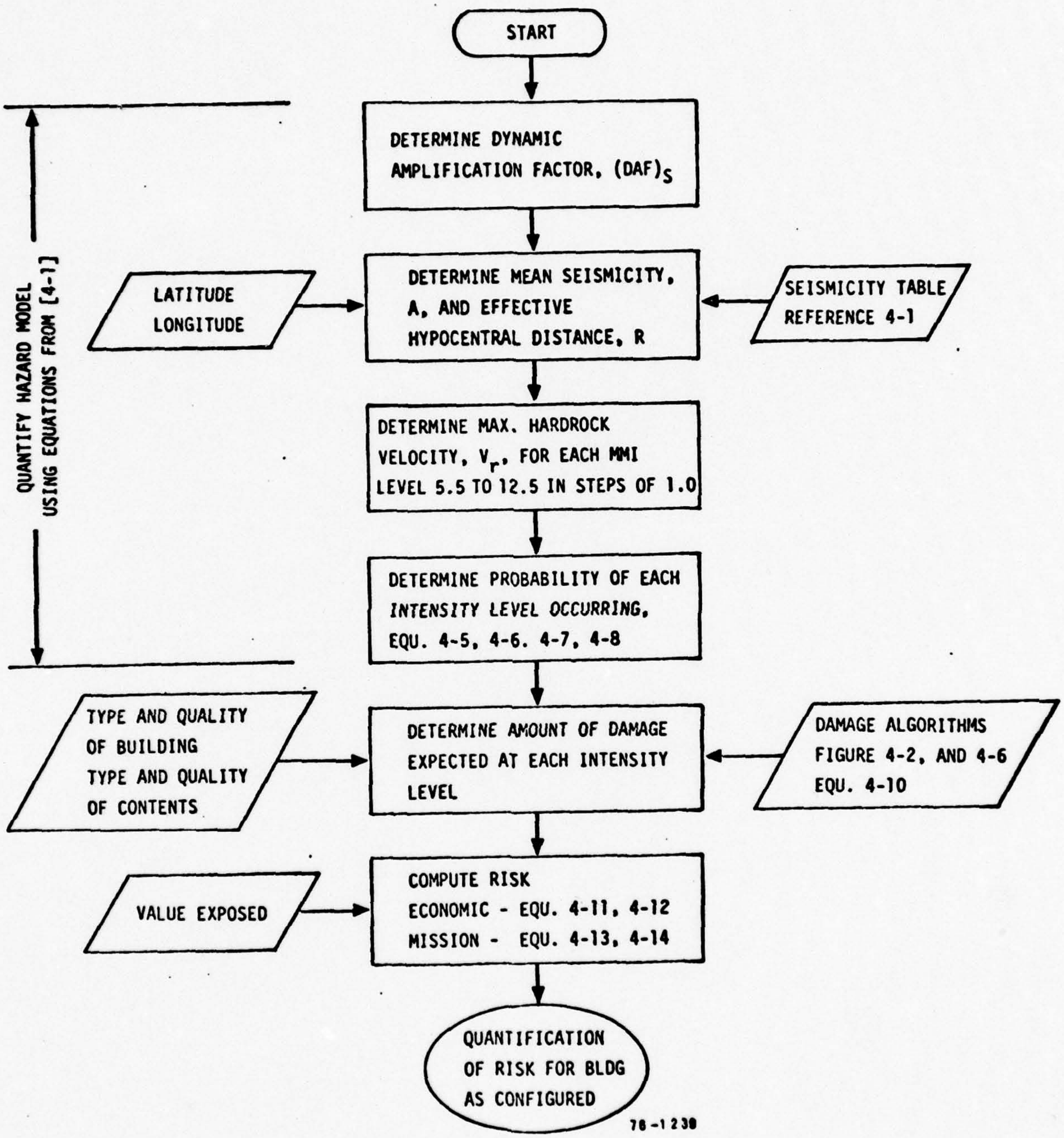

Figure 4-1. Calculation of the Earthquake Hazard Risk

4.2 Hazard Model

The hazard model used for this methodology is based on work previously performed by the J. H. Wiggins Company. The primary data source for the earthquake parameters is Appendix G of the National Bureau of Standards Building Science Series 61. Since the publication of that document [4-1] in January of 1975, additional work has been done to upgrade the data contained therein. When the later work becomes available it will supersede the above reference and should be incorporated into this methodology.

In order to determine the earthquake occurrence probability for a particular site, one must know basically three things:

1) The distribution of seismic energy,
2) The attenuation properties of the earth's crust, and
3) The dynamic amplification of the soil underlying the site.

In the present analysis, the distribution properties of seismic energy relevant to a particular site are expressed in terms of two parameters

$\bar{A}$ = Total site seismicity within a radius of potential damageability

R = Effective hypocentral distance of seismic energy released within that area

In essence, $\bar{A}$ determines the total energy released over a broad area and R determines an effective focal point distance.

The first step in quantifying the earthquake hazard is to determine the seismicity and hypocentral distances at the subject base. This data is given in Appendix G of Reference 4-1 for 1/2° by 1/2° grids covering the contiguous United States, Alaska, and Hawaii.

Two sets of data appear for each grid area, each containing three columns. These are defined as follows:

A(H) = Mean seismicity $\bar{A}$ based on "Historic" data which includes all recorded data up to the year 1961.

O(H) = Standard deviation of seismicity, σ_A, based on "Historic" data.

R(H) = Effective hypocentral distance to the source of a representative earthquake.

The second set of data (specified as A(N), O(N), and R(N)) correspond to the same three parameters except that NOAA data from 1961 to 1973 form the data base in lieu of the "Historic" data prior to 1961.

In most cases, the data which produce the higher probabilities are recommended for use with this methodology.

The second step in evaluating the hazard model is to determine a dynamic amplification factor $(DAF)_s$ for the site. This parameter is a very difficult parameter to characterize. Opinions range from the idea that all sites give random characteristics so it is impossible to model them to the idea that all sites are very predictable in their dynamic behavior[4-2]. Reference 4-1 [pages 3-86 to 3-89] provides a number of ways to compute the parameter $(DAF)_s$, all of which are acceptable for this methodology.

Once the mean seismicity, A the effective hypocentral distance, R and the dynamic amplification factor, $(DAF)_s$ are determined, the probability of occurrence associated with each Modified Mercalli Intensity level from VI to XII must be determined. Using the equations given on pages 3-77 to 3-84 of Reference 4-1, it is possible to calculate the probability of an earthquake of any intensity being experienced.

The steps to be followed are outlined below:

	Source
Determine $(DAF)_s$ for subject facility	[Pages 3-86 to 3-89, 4-1]
Determine mean seismicity, A.	[Appendix G, 4-1]
Determine effective hypocentral distance, R.	[Appendix G, 4-1]

Specify MMI level. Probabilities of occurrence for the following MMI levels* must be calculated:

5.5, 6.5, 7.5, 8.5, 9.5, 10.5, 11.5, 12.5

Calculate the maximum soil particle velocity, V_s, corresponding to each MMI level specified above.

(4-1) $\log_{10} V_s = -1.973 + 0.375\ \text{MMI}$ [Equation 3.4.22, 4-1]

Calculate the maximum hardrock velocity corresponding to each soil particle velocity.

---

*For convenience and mathematical compatibility, the MMI levels are specified as Arabic numerals instead of the more commonly used Roman numerals.

170

(4-2) $V_r = V_s/(DAF)_s$ [Equation 3.4.27, 4-1]

Calculate the Richter magnitude, M, corresponding to each hardrock velocity. Use either of the following two equations, depending on the base location.

Western United States (longitude $\geq$ 105°)

(4-3) $\log_{10}V_r = -1.625 + 0.563\ M - 1.403\ \log_{10}R$

[Equation 3.4.23, 4-1]

Eastern United States (longitude < 105°)

(4-4) $\log_{10}V_r = -2.062 + 0.563\ M - 0.979\ \log_{10}R$

[Equation 3.4.24, 4-1]

Calculate the mean rate of occurrence, λ, of earthquakes equal to or greater than each Richter magnitude determined above:

(4-5) $\log_{10}\lambda = A - 0.9M$ [Equation 3.4.12, 4-1]

Having found M for each mid-intensity (i.e., 5.5, 6.5, etc.) specified earlier, the probability of experiencing the intensity level in any year can now be determined. This final step requires that we assume that the earthquake process is a

Poisson process. For a Poisson process the probability of ν events in time t is given by

$$P_\nu = \frac{(\lambda t)^\nu}{\nu!} e^{-Nt} \qquad \text{(4-6)} \qquad \text{[Equation 3.2.4, 4-8]}$$

The probability of having one or more event is

$$F = \sum_{1}^{\infty} \frac{(\lambda t)\nu}{\nu!} e^{-Nt} \qquad \text{[Equation 3.4.13, 4-1]}$$

With a few simple manipulations it can be shown that this reduces to

$$F = 1 - e^{-\lambda t} \qquad \text{(4-7)}$$

where F is the probability of having one or more events of magnitude equal to or greater than M. M and λ are related by the Equation 4-5; MMI and M are, in turn related by Equations 4-1 through 4-4.

Utilizing Equation 4-8 it is possible to define the probability that each intensity level will be experienced one or more times

$$P_i(MMI_a < MMI < MMI_b) = F(MMI_b) - F(MMI_a) \qquad \text{(4-8)}$$

Criticisms of the assumption that earthquakes are a Poisson process are many and are well documented in the literature on earthquakes. Nevertheless, it is widely used--mainly for the reason which was discussed earlier with respect to the fire hazard. It is the only practical distribution presently available.

4.3 Damage Algorithms

Two approaches have been used to provide damage algorithms applicable to Navy and Marine Corps structures. Approach one is based on work performed at the J. H. Wiggins Company. It is applicable to low rise buildings and single family dwellings. Approach two is based on work performed at the Massachusetts Institute of Technology (MIT) as part of their project on Seismic Design Decision Analysis (funded by the National Science Foundation). This approach is used for multi-story buildings (5 to 20 story) with reinforced concrete frames or shear walls, or steel frames.

4.3.1 Low Rise Buildings

For low rise buildings, and especially single-family residences, considerable information is available concerning damage probability. This information has been used by the J. H. Wiggins Company to develop damage relationships for commercial-industrial and dwelling type structures. These relationships, as shown in Figure 4-2, are applicable to low rise naval shore facilities.

The seven different relationships reflect differences in the types of structures and their quality of construction. A grading process is used to determine which relationship applies. Points are assigned to the structure according to the procedure specified in Section 7.

The building's Quality Index (Q), used to key the building to a particular damage relationship, is determined from the total number of points given to the building:

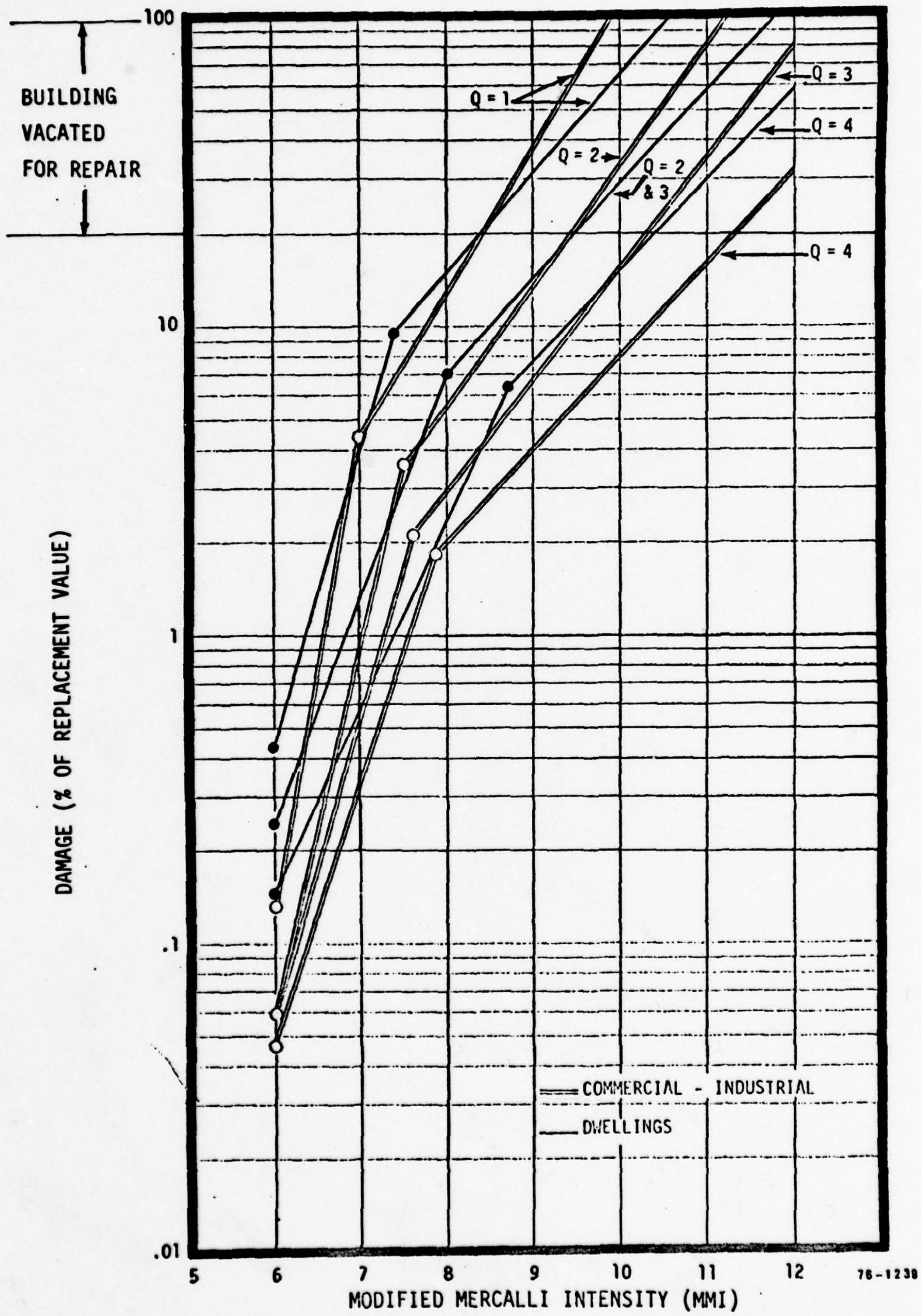

Figure 4-2. Damage Relationships for Commercial/Industrial and Dwelling Structures

CONVERSION OF BUILDING GRADE
POINTS TO BUILDING QUALITY

GRADE FACTOR	MAXIMUM GRADE POINTS	WEIGHTING FACTOR	ADJUSTED TOTAL POINTS
Framing System and/or Walls	50	2.00	100
Diaphragm	50	1.50	75
Partitions	20	1.25	25
Special Conditions	40	1.00	40
Physical Conditions	50	1.80	90
TOTAL	210		330

NUMBER OF POINTS	BUILDING QUALITY	
330 - 280	SPECIAL	4
280 - 200	HIGH	3
200 - 120	AVERAGE	2
120 - 0	LOW	1

The number of grade points for each factor is acquired from the building inspection form discussed in Section 7. For each Quality Index, the $\log_{10}$ of the structural damage (D_{jl}) is piecewise linear in the Modified Mercalli Intensity (MMI).

$$\log_{10} D_{jl} = C + d(MMI) \qquad (4\text{-}9)$$

In this equation, d is considered to be known perfectly. The parameter c is taken to be normally distributed with a standard deviation given by

$$C = 0.141$$

The above standard deviation, C, is not utilized when estimating average annual damage (see Equations 4-11 and 4-12). Only the mean damage, as given by Equation 4-9, is used for this. The standard deviation is available, however, for determining the variability in any loss projections.

4.3.2 High Rise Buildings

The approach used for high rise buildings to quantify the damage/intensity relationship is taken from the work conducted at MIT by Whitman, Biggs, Cornell, Vanmarke, and others [4-4,4-5] Since this approach was applied to other hazards as well, a brief summary of their development of the damage probability matrix (DPM) concept is provided here.

The DPM concept (Figure 4-3) expresses the beneficial effect of increased seismic resistance. The level of damage is described by a series of damage states. Each number in the

matrix is the probability that a particular state of damage will occur given that a certain level of earthquake intensity is experienced.

DAMAGE STATE	CENTRAL DAMAGE RATIO %	MMI INTENSITY				
		VI	VII	VIII	IX	X
O - NONE	0					
L - LIGHT	0.3		P_{DSI}			
M - MODERATE	5					
H - HEAVY	30					
T - TOTAL	100					
C - COLLAPSE	100					

Figure 4-3. Form of Damage Probability Matrix [4-4]

The damage to buildings is described by damage states, while the intensity of the earthquake is described by the Modified Mercalli Intensity (MMI) scale. The sum of the probabilities in each column is one.

There are several reasons why there is uncertainty in the damage caused by a particular intensity:

- Individual buildings, from a group of buildings all designed to meet the same requirements, will have different resistances to earthquake damage depending upon the skill and inclination of the individual designer and contractor.
- The details of ground motion, and hence the dynamic response of identical structures, will differ at different locations all experiencing the same general intensity of ground motion.

Hence, damage to be expected in future earthquakes must be expressed in probabilistic terms. A separate DPM is required for each different set of design requirements, and the differences between these DPM quantify the effects of the design requirments.

Earthquake literature contains many, many descriptions of damage to buildings from past earthquakes[4-9]. From this data it is possible to provide general guidance of expected damage:

	Modified Mercalli Intensity			
Construction	VI	VII	VIII	IX and X
Brick masonry with no planned lateral resistance	some damage	few collapse	many collapse	nearly all collapse
Steel frame with no planned lateral resistance	minor damage	moderate damage	few partial collapse	many partial collapses
Reinforced concrete with minimal earthquake design		some damage	some collapses	many collapses
Reinforced concrete frame with good earthquake design			some collapses	some collapses
Steel frame with good earthquake design		minor damage	some damage	considerable damage

The difficulty is that the words "few, many," etc., are far too imprecise for a systematic design analysis. Unfortunately, the literature on past earthquakes is usually inadequate to provide anything better.

Figure 4-4 shows the damage states developed in the MIT work. Each damage state is defined in two ways: (a) by a set of

EXTENDED DAMAGE STATE	DESCRIPTION	CENTRAL DAMAGE RATIO*	DAMAGE RANGE
0	No damage	0	0 - 0.05%
1	Minor non-structural damage - a few walls and partitions cracked, incidental mechanical and electrical damage	.001	0.05 - 0.3%
2	Localized non-structural damage - more extensive cracking (but still not widespread); possibly damage to elevators and/or other mechanical/electrical components	.005	0.3 - 1.25%
3	Widespread non-structural damage - possibly a few beams and columns cracked, although not noticeable	.020	1.25 - 3.5%
4	Minor structural damage - obvious cracking or yielding in a few structural members; substantial non-structural damage with widespread cracking	.050	3.5 - 7.5%
5	Substantial structural damage - requiring repair or replacement of some structural members; associated extensive non-structural damage	.100	7.5 - 20%
6	Major structural damage - requiring repair or replacement of many structural members; associated non-structural damage requiring repairs to major portion of interior; building vacated during repairs	.300	20 - 65%
7	Building condemned	1.000	65 - 100%
8	Collapse	1.000	100%

*Ratio of cost of repair to replacement cost

Figure 4-4. Extended Earthquake Damage States [4-4]

words describing the degree of structural and non-structural damage and (b) by a ratio of the cost of repairing the damage to the replacement cost of the building. The relationship between the word description and the numerical description was chosen to be consistent with data collected from the San Fernando earthquake of 1971. For the final DPM produced at MIT the nine damage states shown in Figure 4-4 were condensed to six damage states, as shown in Figure 4-5.

DAMAGE STATE INDEX-j	EXTENDED (ORIGINAL) DAMAGE STATES	SHORTENED DAMAGE STATES		
		LEVEL OF DAMAGE	SYMBOL	CENTRAL DAMAGE RATIO
1	0	NONE	0	0
2	1 2	LIGHT	L	.003
3	3 4 5	MODERATE	M	.050
4	6	HEAVY	H	.300
5	7	TOTAL	T	1.000
6	8	COLLAPSE	C	1.000

Figure 4-5. Relation between Extended and Shortened Damage States [4-4]

180

Three approaches were used by Whitman, et al., to quantify the DPM:

- Documentation of actual earthquake damage (Deductive)
- Theoretical analysis (Inductive)
- Judgement (Deductive)

Only DPM's for multi-story buildings with reinforced concrete frames or shear walls, or steel frames were generated. Neither the empirical approach nor the theoretical approach, nor the two taken together, were entirely adequate. Hence, a third approach, judgement, was used to fill gaps in the other estimates, to resolve conflicts, and to account for difficult to qualify benefits. Many of the individual damage probabilities were arbitrarily set, and somewhat different sets of probability values would be equally well justified. The most arbitrary part of the selection process was the breakdown between P_{total} and $P_{collapse}$. The resulting DPM, as used here, is given in Fig. 4-6.

4.3.3 Contents

The J.H. Wiggins Company has developed two formulae for estimating damage to building contents. Inherent in both approaches is the assumption that contents damage D_{j2} is some constant times the structural damage, D_{j1}. Two formulae are proposed for evaluating the constant:

1) based on the Pacific Fire Rating List
2) based on content vulnerability, CQ, building construction type, CT, and number of stories, NS

Approach 2 was selected for this application because it was more adaptable to Navy facilities. The damage equation is

DESIGN LEVEL	DAMAGE* STATE	j	MODIFIED MERCALLI INTENSITY V	VI	VII	VIII	IX	X,XI,XII
UBC 0, 1	NONE	1	100	27	15	0	0	0
	LIGHT	2	0	73	48	0	0	0
	MODERATE	3	0	0	33	20	0	0
	HEAVY	4	0	0	4	41	0	0
	TOTAL	5	0	0	0	34	75	25
	COLLAPSE	6	0	0	0	5	25	75
UBC 2	NONE	1	100	47	20	0	0	0
	LIGHT	2	0	53	50	10	0	0
	MODERATE	3	0	0	29	53	0	0
	HEAVY	4	0	0	1	31	0	0
	TOTAL	5	0	0	0	5	80	60
	COLLAPSE	6	0	0	0	1	20	40
UBC 3	NONE	1	100	57	25	0	0	0
	LIGHT	2	0	43	50	25	0	0
	MODERATE	3	0	0	25	53	20	0
	HEAVY	4	0	0	0	21	52	0
	TOTAL	5	0	0	0	1	23	80
	COLLAPSE	6	0	0	0	0	5	20
SPECIAL	NONE	1	100	67	30	0	0	0
	LIGHT	2	0	33	49	40	10	0
	MODERATE	3	0	0	21	52	30	0
	HEAVY	4	0	0	0	8	58	0
	TOTAL	5	0	0	0	0	2	90
	COLLAPSE	6	0	0	0	0	0	10

*Refer to Figure 4-5 for the corresponding central damage ratios

77-1238

Figure 4-6. Damage Probability Matrix for Multi-Story Concrete Frame or Shear Wall Buildings or Multi-Story Steel Frame Buildings

$$D_{j2} = (0.2 * CQ * CT * NS)\, D_{j1} \qquad (4\text{-}10)$$

D_{j2} = contents damage (limited to 1.0)

D_{j1} = structure damage ratio

CQ = index for content vulnerability

CT = index for construction type

NS = index for number of stories

CQ, CT, and NS are determined as follows using information from the building inspection form (Section 7)

- Content vulnerability

  CQ = 40 - Total Content Grade Points
  (from Inspection Form)
  (Stability + Delicacy + Overhang)

- Construction Type

	CT
Steel Moment Resisting Frame	1.1
Concrete Moment Resisting Frame	0.9
Steel Braced Frame	0.9
Concrete Braced Frame	0.8
Shear Wall	0.7
Frame & Shear Wall	0.7
Wood Shear Wall	0.6
Bearing Wall	1.5
Mobile Home	1.5

- Number of Stories

Number of Stories	NS
1 to 3	1.0
4 to 6	1.1
7 to 12	1.2
13 to 24	1.3
> 24	1.4

4.4 Expected Losses

4.4.1 Economic Losses

Section 4.2 presented the procedure used to obtain the probability of the base being struck by an earthquake of each MMI level. The relationship between expected damage and MMI level is given by either Figure 4-2 or 4-6. The probability damage matrix approach is used for high-rise structures while a deterministic relationship is used for the low-rise structures.

The procedure used to calculate the expected annual average economic loss uses the above information as follows: (see Figure 4-1 also):

- Determine the annual probability of the site being struck by each earthquake intensity level (i.e., the hazard model)
- Determine the corresponding damage or damage states (i.e., the damage algorithm)
- Obtain the total replacement value of the structure and its contents (i.e., the exposure model)
- Determine the expected average annual loss using the following equation for high-rise structures

$$E\langle LOSS\rangle = \sum_{h=1}^{2} \sum_{i=VI}^{XII} \lambda_i \sum_{j=1}^{6} D_{jh}\, P(D_{jh}|P_i) V_h$$

$$= \sum_{h=1}^{2} \sum_{i=VI}^{XII} \lambda_i \sum_{j=1}^{6} D_{jh}\, Q_{ij}\, V_h \qquad (4\text{-}11)$$

where h = index for type of damage

1 = structure damage

2 = contents damage

i = index for intensity levels

λ_i = mean rate of earthquakes of intensity i $\doteq P_i$

P_i = intensity probability [Hazard Model]

j = index for damage state

Q_{ij} = $P(D_{jh}|P_i)$ = probab. of damage state j given the occurrence of earthquake of intensity i (Damage Algorithm)

D_{jh} = ratio of repair cost to total replacement cost

D_{j1} = Central Damage Ratio (Figure 4-5)

D_{j2} = see Equation 4-10

V_n = value exposed (Exposure Model)

For low-rise structures, the damage algorithm is single-valued. Thus the above equation reduces to

$$E\langle LOSS\rangle = \sum_{h=1}^{2} \sum_{i=VI}^{XII} \lambda_i D_{ih} V_h \qquad (4\text{-}12)$$

where D_{ih} = damage ratio

D_{i1} = values taken from Figure 4-2 for each intensity level. D_{i1} depends on structure's Q. See Equation 4-9

D_{i2} = see Equation 4-10

4.4.2 Mission Losses

The mission reliability is a function of all component structures within the mission network as described in Section 6.1. Consequently the reliability of each structure must be determined. This is done as follows:

$$\text{RELIABILITY}^{*} = 1 - \text{Probability of failure}$$
$$= 1 - \text{Probability of structural damage} \geq 20\%$$

High-rise structures

$$\text{RELIABILITY} = 1 - \sum_{i=VI}^{XII} P_i \sum_{j=4}^{6} Q_{ij} \qquad (4\text{-}13)$$

Low-rise structures

$$\text{RELIABILITY} = 1 - \sum_{i=N(Q)}^{XII} P_i \qquad (4\text{-}14)$$

where P_i is defined by Equation 4-5

N(Q) = lowest MMI level yielding 20% structural damage as shown in Figure 4-2. N(Q) depends on structure type (dwelling or commercial/industrial) and quality (Q).

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* for one structure

The building reliability is the probability that the building will remain functional throughout the year. Implicit in the above formulations is the determination that 20 percent or more damage to the structure will cause the building to be vacated, at least temporarily. This is based on Whitman's definition of heavy damage (20 to 65 percent), which requires the building to be vacated during repairs.

4.4.3 Personnel Losses

The quantification of the risk of death and injury from earthquake to the persons in a specific structure is a difficult problem. Just as in the case for fire, the state of the art is not sufficiently advanced to quantify this risk accurately, if at all. Whitman, et al., have, however, proposed casualty rates which can be used. Their figures [4-4], shown below, represent "very gross estimates" because "appropriate data are effectively absent."

Table 4-2. Damage/Casualty Relation for Earthquake[4-4]

DAMAGE STATE	FRACTION OF PEOPLE INJURED WITH (WITHOUT) CONVENTIONAL SUSPENDED CEILINGS AND LIGHT FIXTURES		FRACTION OF PEOPLE KILLED WITH (WITHOUT) CONVENTIONAL SUSPENDED CEILINGS AND LIGHT FIXTURES	
L - LIGHT	0	(0)	0	(0)
M - MODERATE	1/100	(1/500)	0	(0)
H - HEAVY	1/50	(1/75)	1/400	(1/500)
T - TOTAL	1/10	(1/20)	1/100	(1/150)
C - COLLAPSE	MOST*		1/4	(1/4)

*Assume "most" = 3/4.

Although these rates differentiate between buildings with and without conventional (i.e., not specially designed for dynamic earthquake effects) suspended ceilings and light fixtures, the "confidence in the quantitative difference is, of course, very low."

The casualty rates given above can be combined with the damage probability matrices in Figure 4-6 to provide a casualty rate for each UBC design level. A set of these casualty rates is shown below for the fraction injured and killed with conventional ceilings and light fixtures.

DESIGN LEVEL	MODIFIED MERCALLI INTENSITY					
	V	VI	VII	VIII	XI	X*
UBC 0,1	0	0	.0113	.0817	.2625	.588
UBC 2	0	0	.0031	.0240	.2300	.360
UBC 3	0	0	.0025	.0105	.0729	.230
UBC S	0	0	.0021	.0068	.0166	.165
RATE = No. injured per person in building.						

*Or greater.

Figure 4-7. Injury Rate for Earthquake (Conventional Ceilings and Light Fixtures) [4-4]

DESIGN LEVEL	MODIFIED MERCALLI INTENSITY					
	V	VI	VII	VIII	IX	X*
UBC 0,1	0	0	.0001	.0169	.0700	.190
UBC 2	0	0	.00002	.0038	.0580	.106
UBC 3	0	0	0	.0006	.0161	.058
UBC 5	0	0	0	.0002	.0016	.034
RATE = No. killed per person in building.						

*Or greater.

Figure 4-8. Death Rate for Earthquake (Conventional Ceilings and Light Fixtures) [4-4]

The above figures provide casualty rates which may be used to evaluate the risk of death and injury from the hazard. However, we recommend that they not be used. Just as was the case with fire and wind, the state of the art does not appear to justify the use of these criteria for decision making at the building level. Whitman himself states that these casualty rates are "still very gross estimates."[4-1] Neither does he provide any justification or basis for these numbers. Certainly the use of death and injury risks is an important tool in making decisions affecting an entire nation, an entire state, or even an entire county. However, to use them for detailed decisions at the building level does not appear to be justified at this time.

The average annual number of deaths and injuries for an entire base could be estimated using these figures. It will differ from base to base depending on the seismic environment. It is expected that at most bases these rates will already be at or below an "acceptable" level (see Section 1.3) of 10^{-9}. Justification of this opinion, however, awaits the completion of some base analyses.

It should also be noted that any actions which reduce the amount of economic loss or mission risk will also reduce the number of deaths and injuries.

4.5 Methodology

The initial input data for earthquake consists of the following types: hazard and damage, exposure and vulnerability, and mitigation and cost. A table of this data is provided in Section 4.1.

To begin the analysis, the structure's identification number must be provided. In addition, the initial seismic design level must be determined. This information, as well as information on construction type, structural quality, content type, and content vulnerability is provided on the building inspection form (Section 7). The initial seismic design level is determined using two different approaches depending on the building's height.

Approach 1 (Figure 4-9) applies to high rise buildings and involves determining the initial design level according to UBC standards. The UBC levels 0,1,2,3, and S correspond to UBC seismic zones 0,1,2,3 and Special. The special zone design level is twice that of zone 3 and was originally introduced by Leslie [4-6] at MIT. Each of these seismic zone levels correspond to a Z coefficient in the UBC base shear formula:

$$V = Z * I * K * C * S * W \qquad (4\text{-}15)$$

where
- V = base shear
- Z = seismicity coefficient
- I = occupancy importance coefficient
- K = horizontal force factor for buildings
- C = numerical coefficient relating to building period
- S = site structure resonance coefficient
- W = total dead load

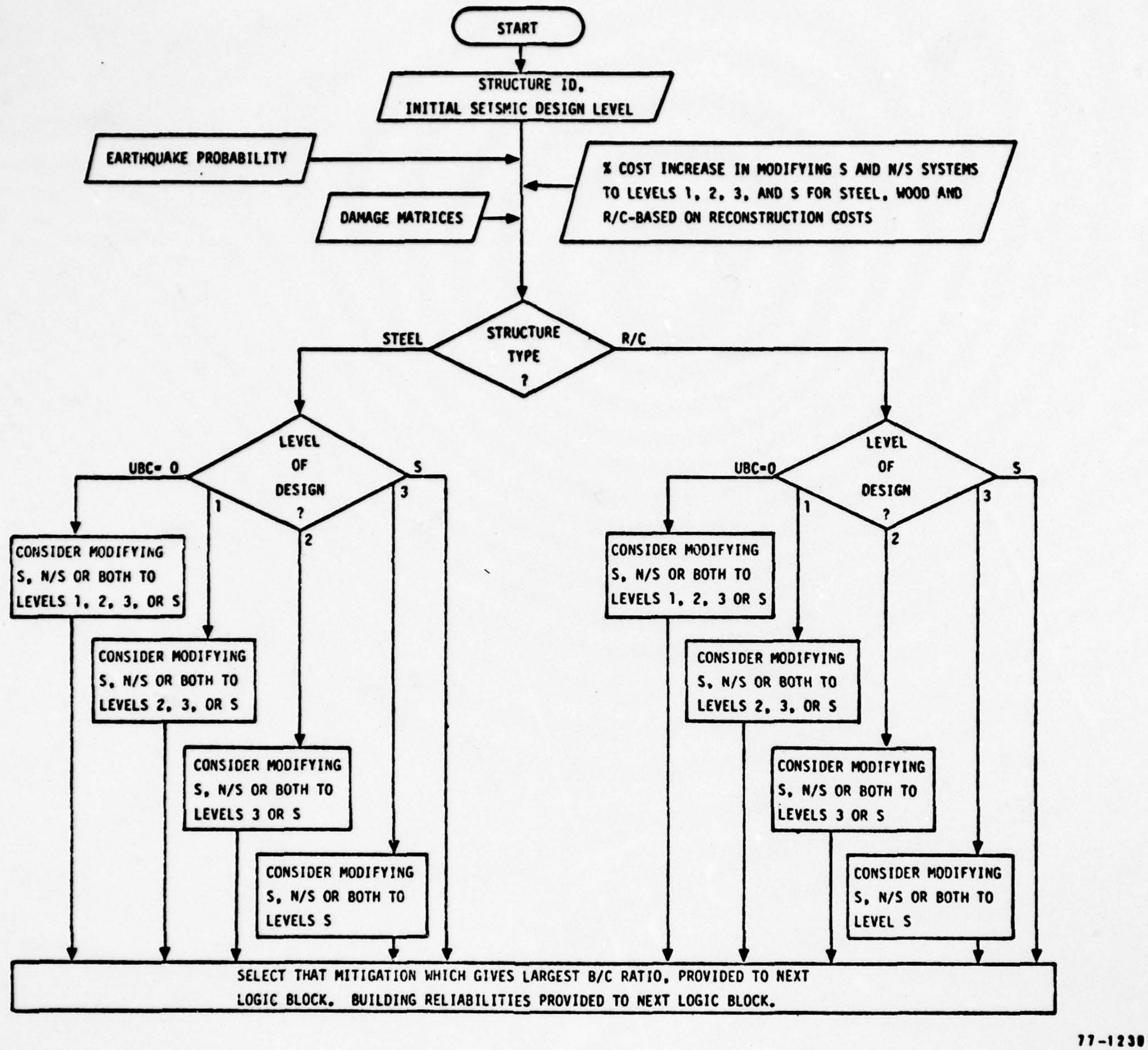

Figure 4-9. Earthquake Hazard - High Rise Structures

AD-A073 157 WIGGINS (J H) CO REDONDO BEACH CALIF F/G 13/13
CAPITAL INVESTMENT PROGRAM FOR MITIGATION OF RISKS FROM NATURAL--ETC(U)
MAY 77 L T LEE, R T EGUCHI, J COLLINS N00025-75-C-0014

UNCLASSIFIED TR-77-1239-1 NL

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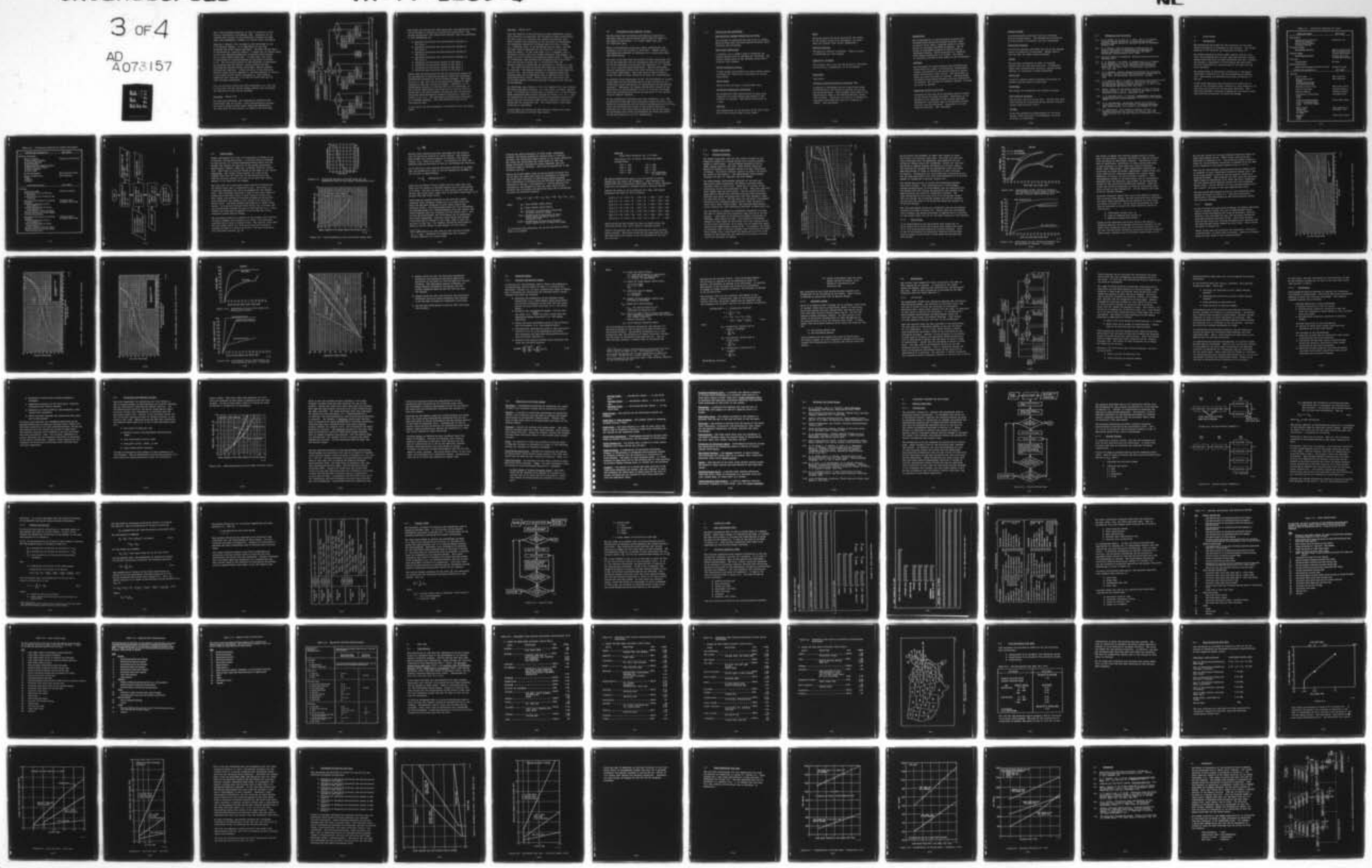

The Z factor becomes important in that it allows for variations in seismicity or earthquake risk. Therefore, by increasing this factor, we can arbitrarily increase our base shear and,consequently, augment out lateral force resistance.

Approach 2 (Figure 4-10) is based on work performed at the J. H. Wiggins Company. It is applicable to low rise buildings and single family dwellings. The basic design level is determined by a Quality Index Q. A single set of indices apply to low rise commercial/industrial structures while another set to single family dwellings. In each case, this index is determined by a grading process as described in Section 4.3.1. The structural quality of the buildings is determined by examining five key factors: framing system and wall, diaphragm and bracing system, partitions, special hazards, and physical condition. Points are given to the structure based on these factors, Appendix C, and then combined to provide a value which can be used to determine Q. The building inspection form (Section 7) is used to record this and all other relevant information.

Once the structure height has been determined (i.e., low rise or high rise) and the initial seismic design level evaluated, the appropriate branch can be followed.

<u>High Rise</u> (Figure 4-9)

For high rise buildings, the construction categories are broken down into two groups: steel and reinforced concrete. The initial seismic design level, which was discussed in the first part of this section, is based on UBC standards.

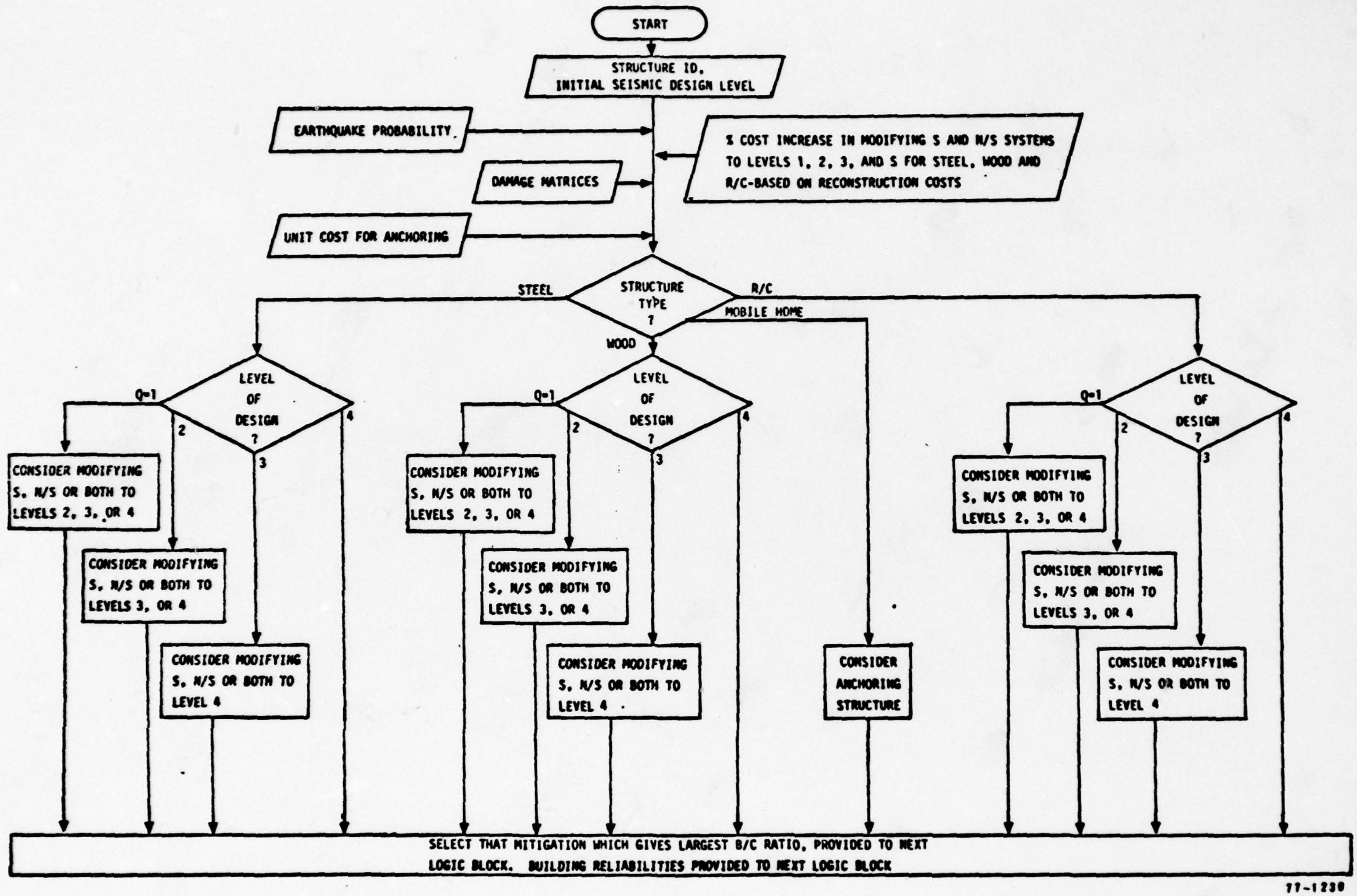

Figure 4-10. Earthquake Hazard - Low Rise Structures

Once these two factors have been determined, the appropriate branch can be followed to examine all mitigating alternatives. The various mitigations, and combinations thereof, that are considered in this methodology are

- modifying structural and non-structural systems to UBC Level 1
- modifying structural and non-structural systems to UBC Level 2
- modifying structural and non-structural systems to UBC Level 3
- modifying structural and non-structural systems to UBC Level S
- modifying non-structural system to UBC Level 1
- modifying non-structural system to UBC Level 2
- modifying non-structural system to UBC Level 3
- modifying non-structural system to UBC Level S

Notice that the modification of the non-structural system can be considered as a separate mitigation, while the structural modification includes all non-structural changes. The reason for this is that the cost of non-structural changes is small compared to that for structural changes. Therefore, it is economically sensible to consider both as one mitigation. If the original construction was steel and its initial level of design was 0, we would consider mitigations that increase the structural and nonstructural systems resistance to those of levels 1,2,3, or S. The same type of methodology would apply to reinforced concrete. The only difference would be the cost factors used.

In any event, the best mitigation is provided to the next logic block.

Low Rise (Figure 4-10)

Once the function of the building has been established (commercial-industrial or dwelling) and the Quality Index Q determined, the next step is to consider all relevant mitigations that would increase the resistance of the structure to earthquakes. For commercial-industrial buildings there are four Q values. Q = 1 indicates that, if an earthquake were to occur, the damage that could be expected for any structure in this class would be severe. On the other hand, a Q = 4 suggests that a structure in this class will suffer relatively less damage. Q equal to 2 and 3 indicate intermediate damage states. Therefore, if a commercial type building were inspected and it was found that the initial Q factor was 1, we determine what the benefit would be in modifying the structure to indices 2,3, and 4. This would be done by noting what reduction in damage could be expected. The expected damages are estimated using equations 4-12 or 4-13. When these reductions in expected damage are combined with the corresponding cost of implementation, they form benefit/cost ratios. These ratios will eventually tell us the best capital investment program in reducing the risk due to earthquakes.

For dwellings, only indices 2 and 3 are combined into one category. The same progressive ordering (i.e., Q=1 worst, Q=4 best) applies here. If a structure original has a Q factor of 1, we can consider those mitigations which would increase the factor to 2 or 4. Like the example for the commercial-industrial building, benefit/cost ratios would be calculated based on the reduction of expected damage and the mitigation cost. For mobile homes, only proper anchoring is considered.

In any event, the mitigation with the best benefit/cost ratio will be provided to the next logic block.

4.6 Availability and Adequacy of Data

The data base (mean seismicity and effective hypocentral distance) used for the earthquake hazard model is based on two types of information: (1) recent (NOAA) data and (2) historical data.

There is considerable uncertainty among seismologists and engineers as to the validity of this data. Indeed, several techniques were employed in Reference 4-1 to ameliorate known data deficiencies.

Not only is the data base the subject of much controversy, but so are the equations used to characterize the site seismicity. All of the constants incorporated into equations 4-1 through 4-9 have been developed empirically. Various techniques, such as regression analysis and curve fitting, have been used by various researchers. There may exist as many different values for some of these constants as there are seismologists.

As pointed out by Algermissen [4-10], the development of seismic zoning maps and the characterizarion of site seismicity is a "relatively recent development in seismological and engineering research." Therefore, the reader should avail himself of the opportunity to read Reference 4-10 so as to better understand this area and the position which the maps hold in this general field of applied research.

As new techniques to determine the site seismicity (i.e., the probability of each MMI level occurring) become available, they should be incorporated into the overall methodology presented here. Since the seismicity data given in the primary reference, Reference 4-1, only covers the 50 states of the United States, the earthquake risk cannot be determined for naval facilities in foreign countries or in U.S. possessions.

4.7 Definitions for Earthquake

Amplification, Dynamic Amplification Factor

The increase in amplitude that may occur in seismic waves as they enter and pass through different earth materials and structures.

Base Shear Coefficient

A constant (i.e., number) used to determine the lateral design force at the base of a building. The lateral design force is the building weight multiplied by this constant.

Damage Probability Matrix

A table giving the probabilities that various levels of damage will result from earthquakes of various intensities.

Damage Ratio

Ratio of cost of repair to replacement cost.

Earthquake Occurrence Probability

The probability that ground motion of some given intensity will occur during some period at the facility of interest. The period used herein is 1 year.

Faulting

The displacement of two portions of the earth relative to one another along a fault plane.

Focus

The point within the earth which marks the origin of the elastic waves of an earthquake; the point where the rupture first occurs (hypocenter).

Hardrock Velocity

The particle velocity in bedrock. Used as a base in developing all site motions.

Hypocentral Distance

The distance from a site on the surface of the earth to the focus, or hypocenter, of an earthquake.

Hypocenter

(See Focus)

Intensity, Modified Mercalli Intensity (MMI)

A measure of earthquake size at a particular place as determined by its effect on persons, structures, and earth materials. The principla scale used in the United States today is the Modified Mercalli Scale, 1956 revision. Intensity is a measure of effects as contrasted with magnitude which is a measure of energy. (See Magnitude)

Liquefaction

The transformation of unconsolidated or poorly consolidated water-saturated granular material (such as sand or silt) into a liquefied state as a consequence of increased pore-water pressures. The increase in pore-water pressure is often caused by earthquake shaking. Earth materials in a liquefied state behave essentially as a liquid. The effect on structures located in such areas can be catastrophic.

Lurching

Over stressing of ground materials by earthquake generated waves can result in deformation, displacement, cracks, and fissures in the ground surface at places other than directly along faults. This phenomenon is known as ground lurching or lurching. Unconsolidated and poorly consolidated materials are most susceptible to lurching, but in areas of intensive shaking, lurching can occur in bedrock.

Magnitude, Richter Magnitude

A measure of the size of an earthquake which is based on the amount of energy released. Technically it is defined as the logarithm or the maximum amplitude recorded of a particular type of seismograph located 62 miles from the epicenter. Magnitude is not the same as intensity. (See Intensity)

Poisson Process

A counting process generally used for relatively rare and random events. The mathematical formulation of this process is conveneint and well understood.

Regression Analysis

Statistical analysis used where the sum of the squared errors in predicting is minimized. Method used to find the best fit among random variables.

Seiche

The periodic oscillation of water in confined basins, such as lakes and reservoirs. Earthquakes often cause seiches either directly, through ground shaking, or indirectly, through landslides.

Seismicity

A term or parameter which represents the amount of seismic activity within a given area.

Seismology

The science of earthquakes and related phenomena.

Soil Particle Velocity

The particle velocity of the soil. Derived from hard-rock velocity by attenuating motion upwards through a dynamic amplification factor.

Tsunami

A sea wave produced by displacements of the ocean bottom, often the result of earthquakes, volcanic activity, or landslides.

4.8 References for Earthquake

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4-4. R. V. Whitman, J.M. Biggs, J. Brennan III, C. A. Cornell, R. de Neufville, and E. H. Vanmarke, "Methodology and Pilot Application", Seismic Design Decision Analysis Report No. 10, Mass. Inst. of Technology, (MIT-CE-R74-15), July 1974.

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4-6. S. K. Leslie, and J. M. Biggs, "Earthquake Code Evaluation and the Effect of Seismic Design on the Cost of Buildings," Seismic Design Decision Analysis Report No. 2, Mass. Inst. of Technology (MIT-CE-R72-20), May 1972.

4-7. SEAOC, "Report of the Ad Hoc Committee on Cost of Design for Earthquake," O.S.T. Task Force on Earthquake Hazard Reduction, San Francisco, September 1970.

4-8. J. R. Benjamin and C. A. Cornell, <u>Probability, Statistics and Decision for Civil Engineers</u>, McGraw-Hill Book Company, 1970.

4-9. K. V. Steinbrugge, "Earthquake Damage and Structural Performance in the United States," <u>Earthquake Engineering</u>, Prentice-Hall, R.L. Wiegel, ed., Chapter 9, 1970.

4-10. S. Algermissen, "The Problem of Seismic Zoning, " in Building Practices for Disaster Mitigation, Building Science Series 46, National Bureau of Standards, February 1973.

5. FLOOD HAZARD

5.1 Introduction

The methodology developed for the evaluation of the flood hazard mitigations is discussed in this section. The salient features of the approach are summarized in Table 5-1.

The damage probability matrix (DPM) concept used for fire, wind, and earthquake has not been used here because existing damage algorithms have not been formulated this way. However, the concept is applicable to flood damage and flood DPM's could be developed from existing data if the data and time were available.

The hazard model is discussed in Section 5.2, the damage algorithms in Section 5.3, and the methodology in Section 5.5. Definitions and References are given in Section 5.7 and 5.8.

A flow chart describing the calculation of flood risk is shown in the following figure (Figure 5-1) even though all of the terms and blocks have not yet been described. This chart may provide a convenient roadmap for the reader during the following discussions of hazard and damage.

Table 5-1. Information Required for Flood

HAZARD AND DAMAGE	DATA SOURCE
Hazard Model	
Depth/Probability Relation ● Riverine Flooding ● Storm Surge Flooding ● Tsunami Flooding	Base Master Plan
Structural Damage	
Depth/Damage Relations	CE[5-10, 5-12] and FIA [5-3, 5-10] data with In-House Modification
Contents Damage	
Depth/Damage Relations	FIA Data [5-3] with In-House Modifications
Life Loss	
Casualty Rate	Not Used
Mission Reliability	
Damage Level Assigned to Mission Failure	Assigned In-House
EXPOSURE AND VULNERABILITY	DATA SOURCE
Building	
Structure Age	Base Inspection
Type of Construction ● Steel ● Reinforced Concrete ● Ordinary Wood Frame	Base Inspection
Elevation of First Floor	Public Works Office
Area of First Floor	Property Inventory
Number of Stories	Property Inventory
Is Structure in Flood Plain ● Yes ● No	Base Master Plan
Is Structure Flood Proofed ● Yes - To Keep Out Water ● Yes - To Minimize Damage ● No	Public Works Office
Type of Flood ● Riverine ● Storm Surge ● Tsunami	Base Inspection or Base Master Plan
Basement ● Yes ● No	Public Works Office

Table 5-1. Information Required for Flood (Continued)

EXPOSURE AND VULNERABILITY	DATA SOURCE
Building (Continued)	
Value of Contents ● Class 3 and 4 Property ● Inventory Material ● Minor Property ● Commissary and Exchange Property ● Special Services Property ● Surplus Property ● Clubs, Other	Property Control Office
Mission Assignments	Base Functional Charts
Content Susceptibility ● Low ● Medium ● Severe	Base Inspection

MITIGATIONS AND COST	DATA SOURCE
Cost Data	
Construction Costs ● Replacement Cost for Existing Structures ● Original Cost for Proposed or New Structures	Property Inventory
Mitigation Cost Factors for Proposed Structure ● Elevating Structure on Fill (area <3000 ft.) ● Elevating Structure on Stilts (area <3000 ft.) ● Flood Proofing to Keep Out Water ● Flood Proofing to Minimize Damage ● Constructing Levees	FIA Report [8-7] CE Reports [8-6, 8-8]
Mitigation Cost Factors for Existing Structure ● Elevating Structure on Fill (area <3000 ft.) ● Elevating Structure on Stilts (area <3000 ft.) ● Flood Proofing to Keep Out Water ● Flood Proofing to Minimize Damage ● Constructing Levees	FIA Report [8-7] CE Reports [8-6, 8-8]

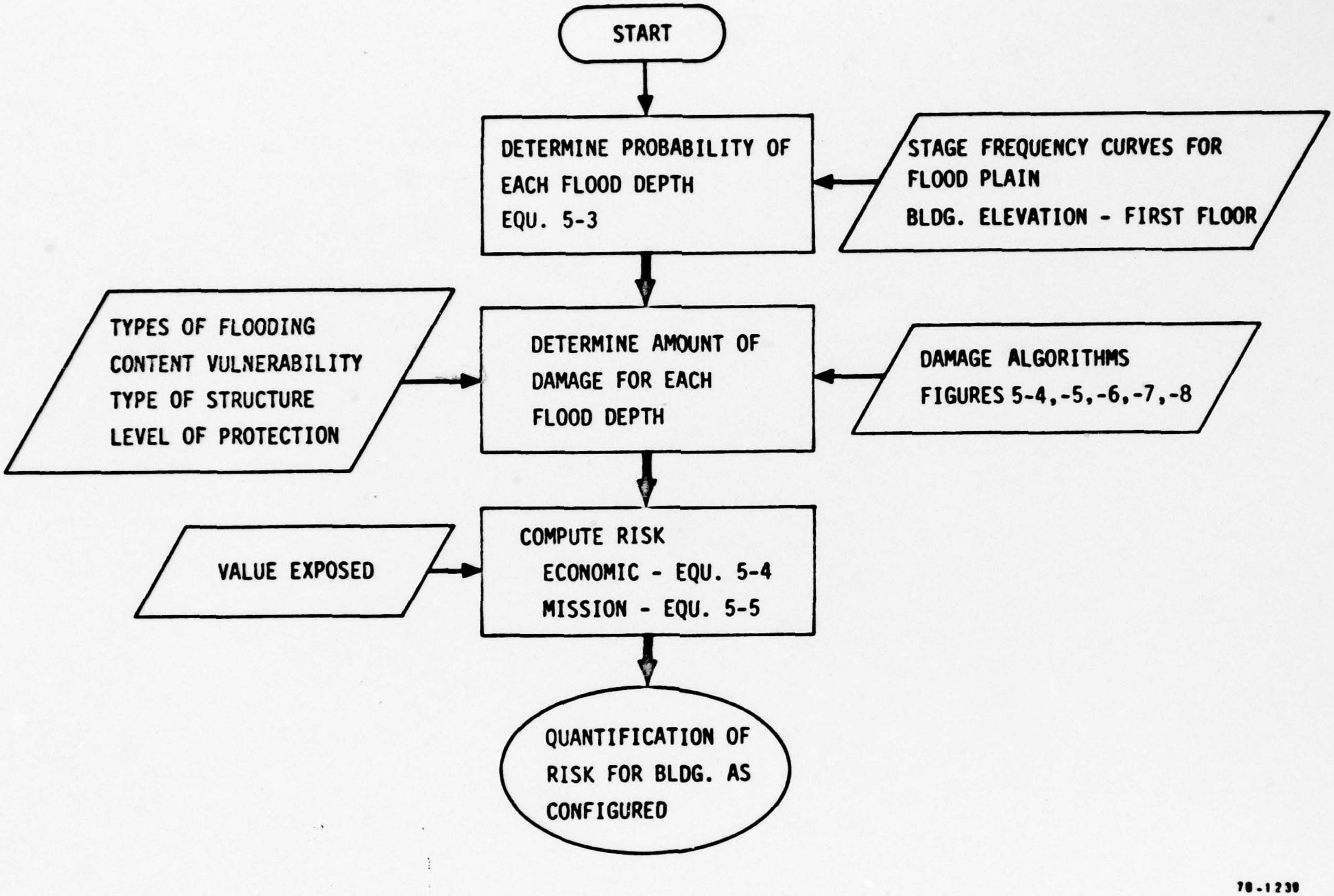

Figure 5-1. Calculation of the Flood Hazard Risk

5.2 Hazard Model

Unlike earthquakes and fires, the occurrence of floods is not a discrete, discontinous event. A riverine flood is defined as that portion of a stream hydrograph during which time the stream flow exceeds the capacity of the normal watercourse. Hydrologists, however, often use a slightly different difinition. They refer to riverine floods as the peaks on the stream hydrograph. The "annual flood series" is a list of the highest flow level for each year in the series while the "partial duration series" is a list of all peak flow levels whether or not they were the highest.

The flow level of a particular stream cannot be predicted by any method other than a probabilistic one. To do this, an integrated histogram must first be prepared for the subject area. This histogram represents a plot of the total number of floods above the lower limit of each interval (Figure 5-2). With longer time periods of recorded information and smaller flow increments, the example curve (Figure 5-2) would be a smooth ogive. The above example was based on an annual flood series. If a partial duration flood series was utilized, the curve would have remained the same at the high end (i.e., large floods) but would have increased at the low end due to the inclusion of more smaller floods.

The recurrence interval is defined as the average time interval, in years, between the occurrence of a flood of a specified magnitude and an equal or larger flood. For example, given that the mth largest flood in a data series has been equaled or exceeded m times in a period of N years, the best estimate of its recurrence interval, t_p, is

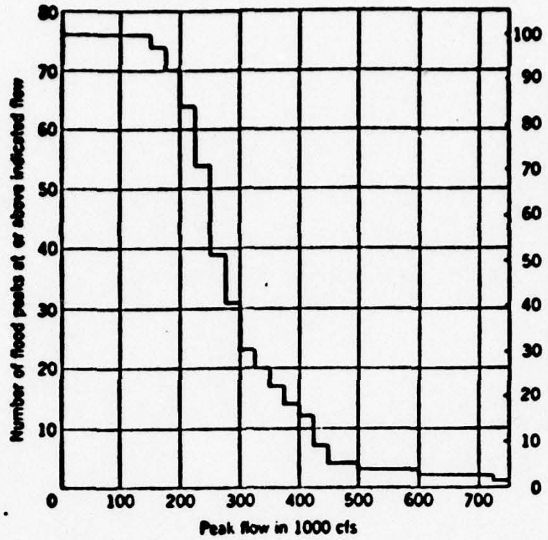

Figure 5-2. Integrated Histogram of Flood Peaks for the Susquehanna River at Harrisburg, Pennsylvania [5-1]

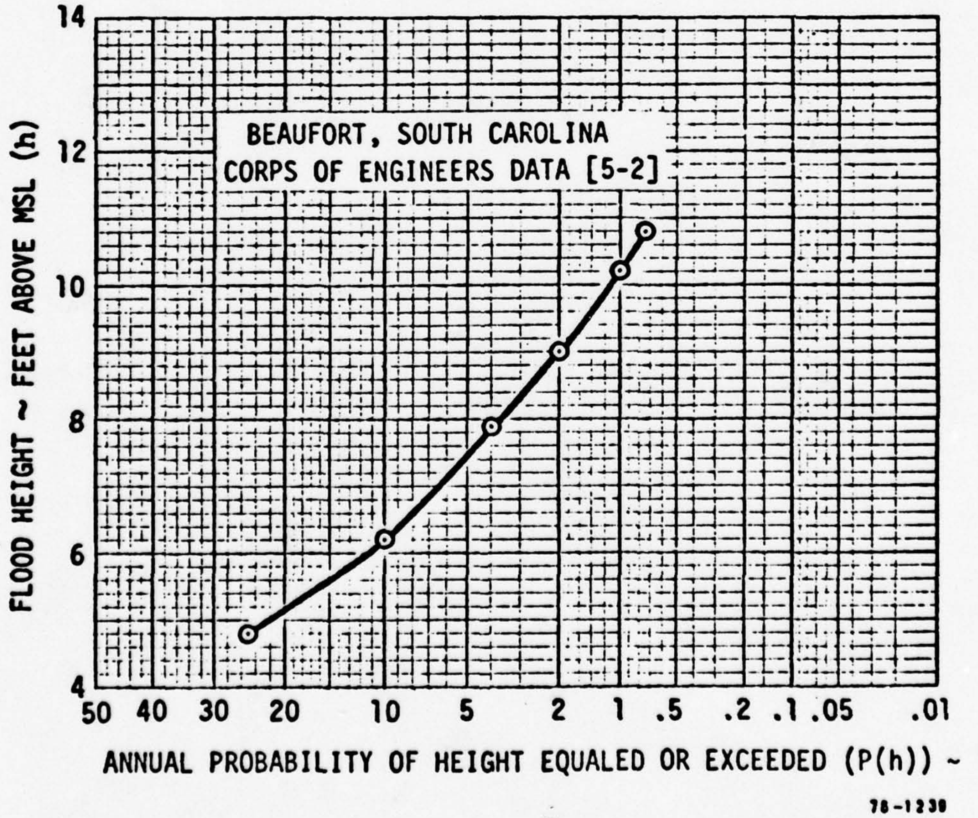

Figure 5-3. Depth-Probability Curve for Parris Island MCRD

$$t_p = \frac{N+1}{m} \tag{5-1}$$

Several other formulas have been developed for the computation of recurrence interval or return period. The disagreement between the various formulas is limited to the larger floods, (i.e., where m is small). If m equals 5 or more, the computed plotting positions of each of the methods are identical.

If an event has a true average recurrence interval of t_p years, then the probability P that it will be equaled or exceeded in any one year is approximately

$$P \doteq \frac{1}{t_p} \quad \text{[Reference 5-1]*} \tag{5-2}$$

Note that the phrase "N-year flood" does not imply that this flood will be equaled or exceeded exactly once in every period of N years. All that is meant is, that given a very long time period, say 10,000 years, there will be 10,000/N floods equal to or greater than the N-year flood.

Flood data are usually presented in the form of a stage-frequency curve (example, Figure 5-3) or a table where the peak flow has been converted to water depth (above some reference level). The flood hazard model for this methodology utilizes the concept of a stage-frequency curve and assumes that stage-frequency data are available for the subject base. Just as with the wind hazard, the flood hazard can be subdivided into three categories: riverine, storm surge, and tsunami. A few bases may be subject to all three, some to only two, and most to only one. For example, the Marine Corps Recruit Deport at Parris Island is only subject to storm surge.

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*This approximation is used with all four hazards provided $t_p >> 1$ year. Otherwise the probability for a Poisson Process (equation 2-1) can be used.

Although the above discussion of flood stage, recurrence interval, and annual probability focuses only on riverine flooding, the conclusions apply equally to all three categories. The reason for subdividing the flood hazard is that the damage algorithms utilized are highly dependent upon the different types of flooding. This will be pointed out in the following section.

Before the hazard model (such as the one given in Figure 5-3) can be used, one additional piece of information is required: the first floor elevation of the building being analyzed. This information is obtained form the building inspection form described in Section 7 and Appendix C. Having obtained this information, the probability that the water level at the building will be between any specified range can be determined by using the following equation

$$P_i(h_a < h < h_b) = P(h > h_a + h_f) - P(h > h_b + h_f) \qquad (5\text{-}3)$$

where

h_a = lower height (above floor)

h_b = upper height (above floor)

h_f = elevation of first floor (above msl or other reference datum)

$P(h)$ = probability of occurrence of water level (above reference level) in specified range

$P_i(h)$ = probability of occurrence of water level (above floor) in specified range

To illustrate this procedure, let us use the Parris Island MCRD as an example.

Bldg 131

First Floor Elevation (h_f = 5.0 feet)

From Figure 5-3, we obtain the following depth probabilities

P(5) = .220	(9) = .020
P(6) = .115	(10) = .012
P(7) = .065	(11) = .006
P(8) = .037	(12) = not available, so assume zero

The above probabilities apply to all structures on Parris Island that lie within the floodplain. They represent the probability that a particular depth above MSL or other reference plane will be equaled or exceeded within a one-year period.

Because the floor is at an elevation of 5 feet, the hazard parameters for Bldg 131 are as follows:

$$P_1(0 \le h < 1) = P(h > 5) - P(h > 6) = .220 - .115 = .105$$
$$P_2(1 \le h < 2) = P(h > 6) - P(h > 7) = .115 - .065 = .050$$
$$P_3(2 \le h < 3) = P(h > 7) - P(h > 8) = .065 - .037 = .028$$
$$P_4(3 \le h < 4) = P(h > 8) - P(h > 9) = .037 - .020 = .017$$
$$P_5(4 \le h < 5) = P(h > 9) - P(h > 10) = .020 - .012 = .008$$
$$P_6(5 \le h < 6) = P(h > 10) - P(h > 11) = .012 - .006 = .006$$
$$P_7(6 \le h < 7) = P(h > 11) - P(h > 12) = .006 - 0 = .006$$

These values are the probability that any depth within the specified limits will occur within a one-year period.

Similar calculations have to be performed for every building being analyzed. The center point of each range shall be used for determining the damage as will be discussed in the next two sections.

5.3 Damage Algorithms

5.3.1 Riverine Flooding

The damage algorithms used here for flood are based on the classical concept of a single valued curve relating percent damage to water depth. The new damage probability matrix (DPM) concept used for the other three hazards should be adopted to flooding to properly reflect the real uncertainty in damage. This would, however, require an effort far beyond the scope of this project. The depth-damage relationships (Figures 5-4 and 5-5) represent the mean damage.

The depth-damage relationships selected for use here are essentially those produced by the Federal Insurance Administration (FIA) in 1975 [5-3]. These are a re-issue of the preliminary curves first published in 1970. They give generally lower damage than the 1970 curves. The FIA curves are only applicable to residential and small business type structures. Although many naval structures fall into this category, there are many that do not. The FIA curve for one-story, no-basement structures was increased slightly below 6 feet to obtain a curve with a more uniform slope. The selected depth-damage curves (Figure 5-4) were previously published in Reference 5-10.

The variability in damage to residential structures is great, but that to commercial and industrial type facilities is even greater. Some types of occupancy are highly susceptible to flooding, while others are not. The problem of estimating damages to these types of facilities, which are representative of most naval facilities, is so acute that no agency has developed general depth-damage curves [5-8]. For example, the Corps of Engineers (CE) in Mobile, Alabama, when estimating Hurricane Betsy damage [5-5], interviewed the owners or operators of 85 percent of the commercial and industrial facilities to obtain individual estimates of damage.

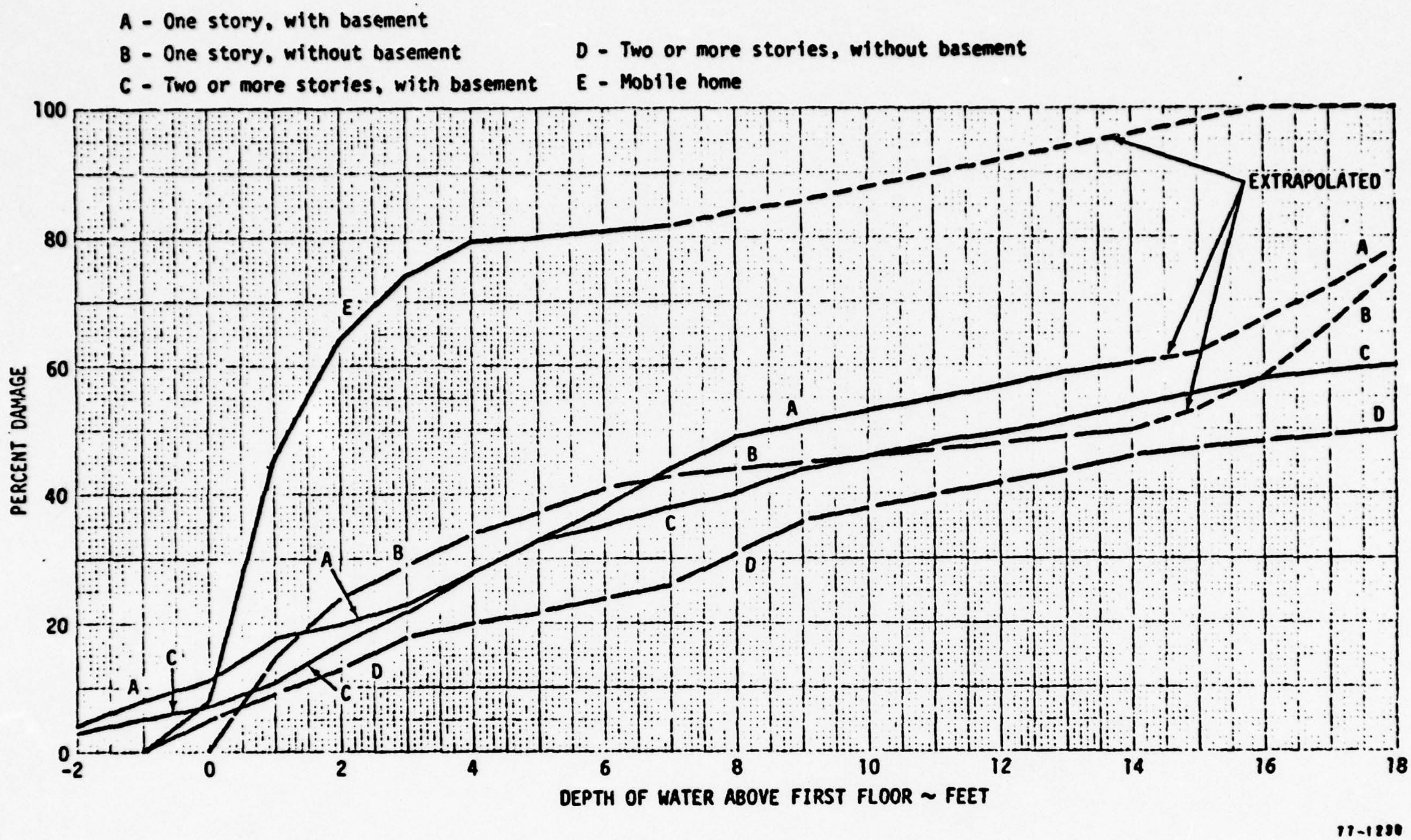

Figure 5-4. Depth-Damage Curves (Riverine Flooding) for Structures Based on Data from Federal Insurance Administration [5-3]

To circumvent this problem, at least with respect to naval facilities, two decisions were made. The first was that most naval structures will be adequately represented by the FIA structural damage curves for residences. Except for high rise buildings or special purpose buildings such as power plants, the construction features of non-residential naval structures seem very similar to those of residential or small business structures. Consequently for non-residential structures we will use the most applicable curve from those presented for structural damage to residential buildings (Figure 5-4).

The second decision was to divide non-residential contents into three classes: high susceptibility to flood damage, average susceptibility to flood damage, and low susceptibility. The damage curve for average susceptibility was assumed to be represented by the curve for residential contents. The high susceptibility curve was taken to be 80 percent larger than the average (at 50 percent damage), and the low susceptibility curve was taken to be 80 percent below the average (at 50 percent damage).

The resulting damage curves for residential and non-residential contents are given in Figure 5-5. Notice that for non-residential contents, the damage percentage is applied only to contents on the subejct floor and not to the total contents in the building.

5.3.2 <u>Storm Surge</u>

It is acknowledged by all researchers that losses due to storm surges are considerably greater than losses that would occur with corresponding depths of riverine flooding. This is due to the destructive capability inherent with the high kinetic energy levels of the initial surge and accompanying wave action.

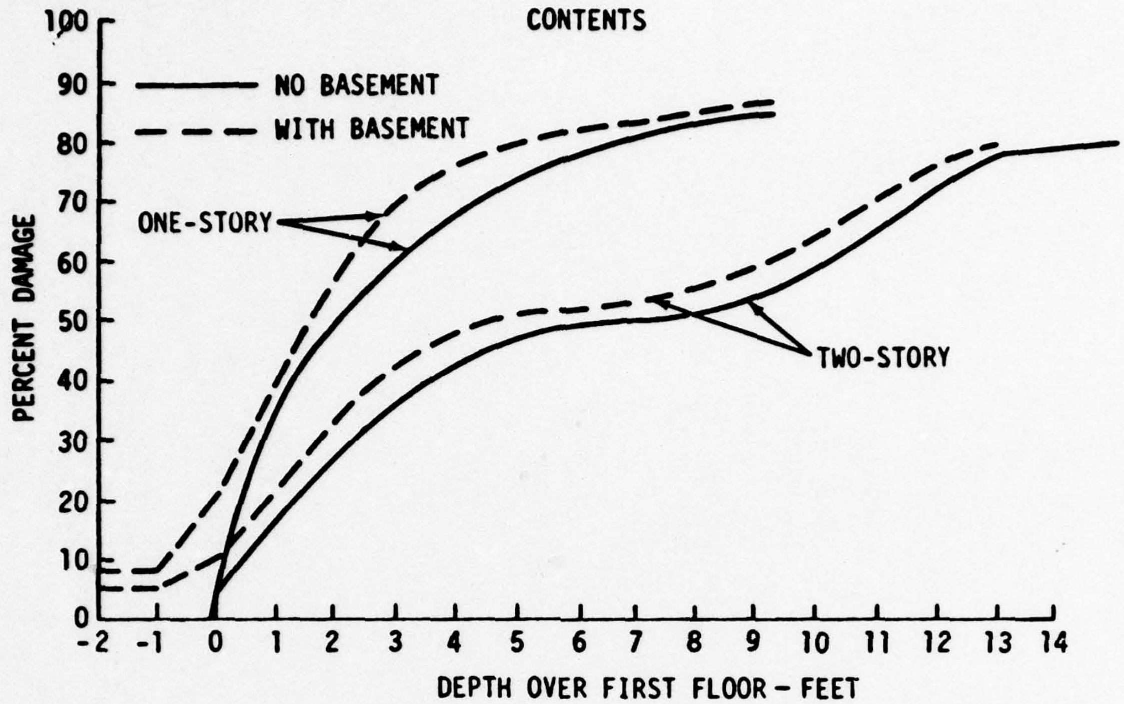

Figure 5-5a. Depth-Damage Curves (Riverine Flooding) for Residential Contents Based on Data from Federal Insurance Administration [5-3]

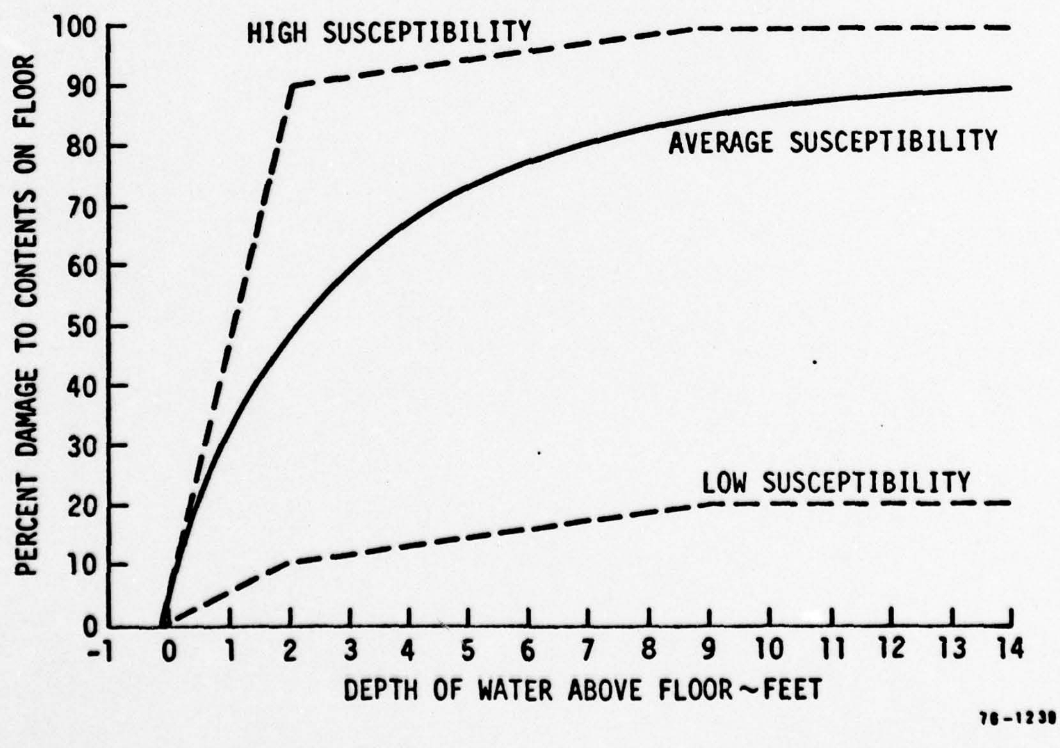

Figure 5-5b. Depth-Damage Curves (Riverine Flooding) for Non-Residential Contents - Postulated

The extent of damage that results depends mainly on storm path, forward speed, intensity and duration, type of construction, and degree of development exposure. Improvements situated on beachfronts, lakefronts, or other unprotected areas in near proximity to large open-water bodies frequently suffer total destruction. Those improvements afforded the protection of nearby buildings, embankments, wooded areas, and other obstructions, experience damages to a lesser degree depending, of course, on the particular situation. Other developments located in low-lying areas, but at considerable distances from the shoreline, are subject to the moderating effects of the intervening marshes and lowlands. These may reduce the flooding conditions to those of slow-rising water with no surge or wave damage[5-4]. Similar effects have been noted for tsunami damages.

Although "everyone" agrees that storm surge damage is greater than riverine flood damage, few have quantified this difference. The storm surge depth-damage curves selected for this study are shown in Figure 5-6. Three curves are provided for each type of structure to account for three different levels of wave action:

- "Stillwater" damage only, or
- Light to Moderate Wave Action, or
- Moderate to Heavy Wave Action.

Damage curves generated from actual data by the Corps of Engineers District in New Orleans [5-4] were available for the above three categories, plus one for riverine flooding, and for one- and two-story residential structures without basements. These curves, together with the Friedman damage model [5-11],

and the FIA curves for riverine flooding formed the basis for these depth-damage curves. These curves were previously published in Reference 5-10. The structural-damage relationships for non-residential structures is assumed to be the same as for residential structures (Figures 5-6a, b, and c).

When the CE (New Orleans) storm-surge structural damage curve is compared to their fresh-water-inundation damage curve, the storm surge damage is about 60 percent greater (based on a weighted average). This compares very well with the Hurricane Betsy damage in Mississippi [5-5] where the total inundation and wave damage was 65 percent greater than the unundation damage alone. The CE (Mobile) data for Hurricane Betsy [5-5] may, however, be based on the same depth-damage curve.

The postulated depth-damage curves for non-residential occupancies are given in Figure 5-7. They were arbitrarily determined in the same manner as the non-residential curves for riverine flooding.

5.3.3 Tsunami

As for riverine and storm surge flooding, the damage algorithms used for tsunami consist of a set of depth-damage curves. Damage curves developed by the Corps of Engineers, Honolulu District, were available for one- and two-story residential structures without basements [5-12]. Their data together with the FIA curves for riverine flooding formed the basis for the depth-damage curves adopted for this study. These curves are shown in Figure 5-8.

Actual curves were not available for commercial, industrial-transportation, or mobile home structures. These were approximated for this study in the following manner:

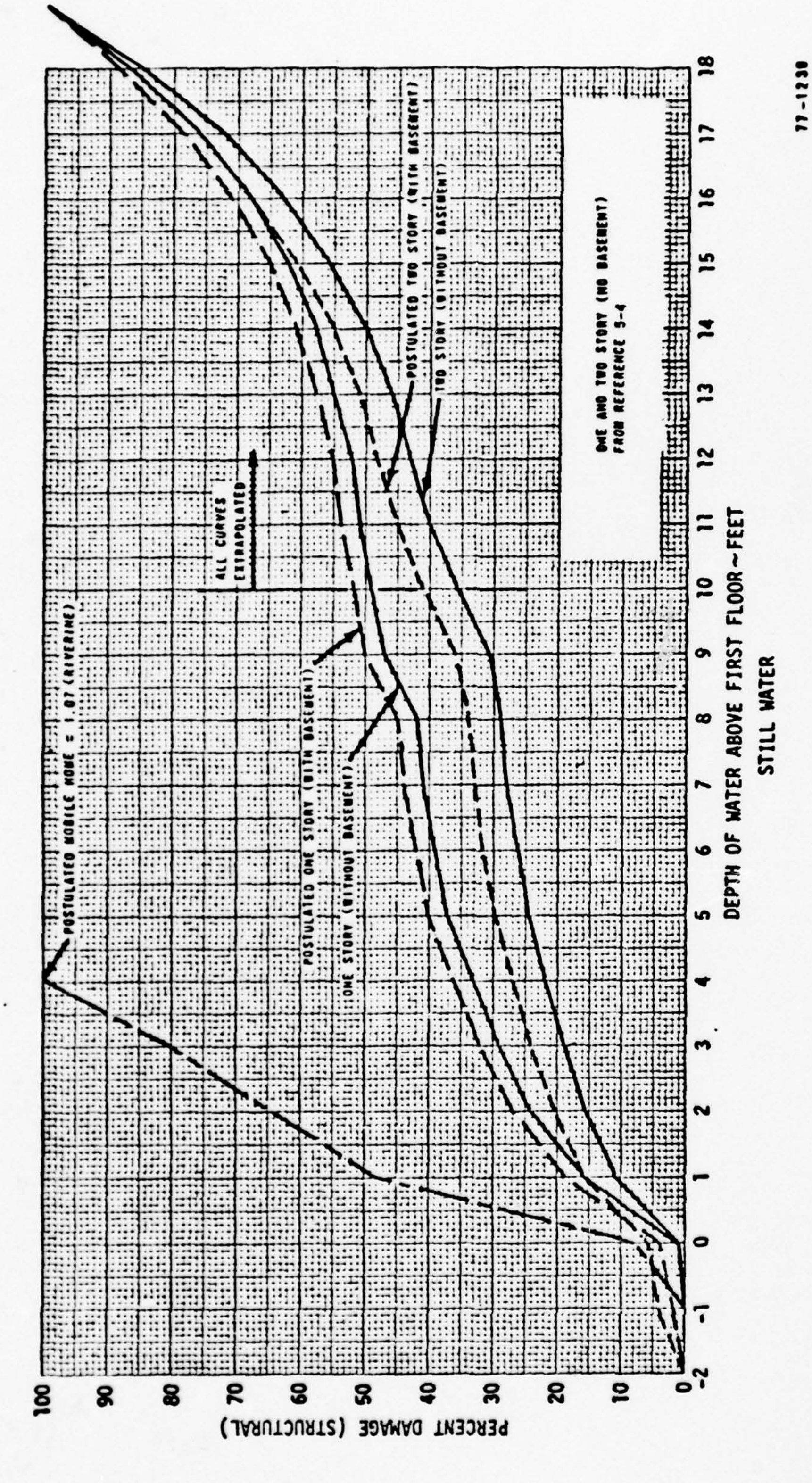

Figure 5-6a. Depth-Damage Curves (Storm Surge) for Structures

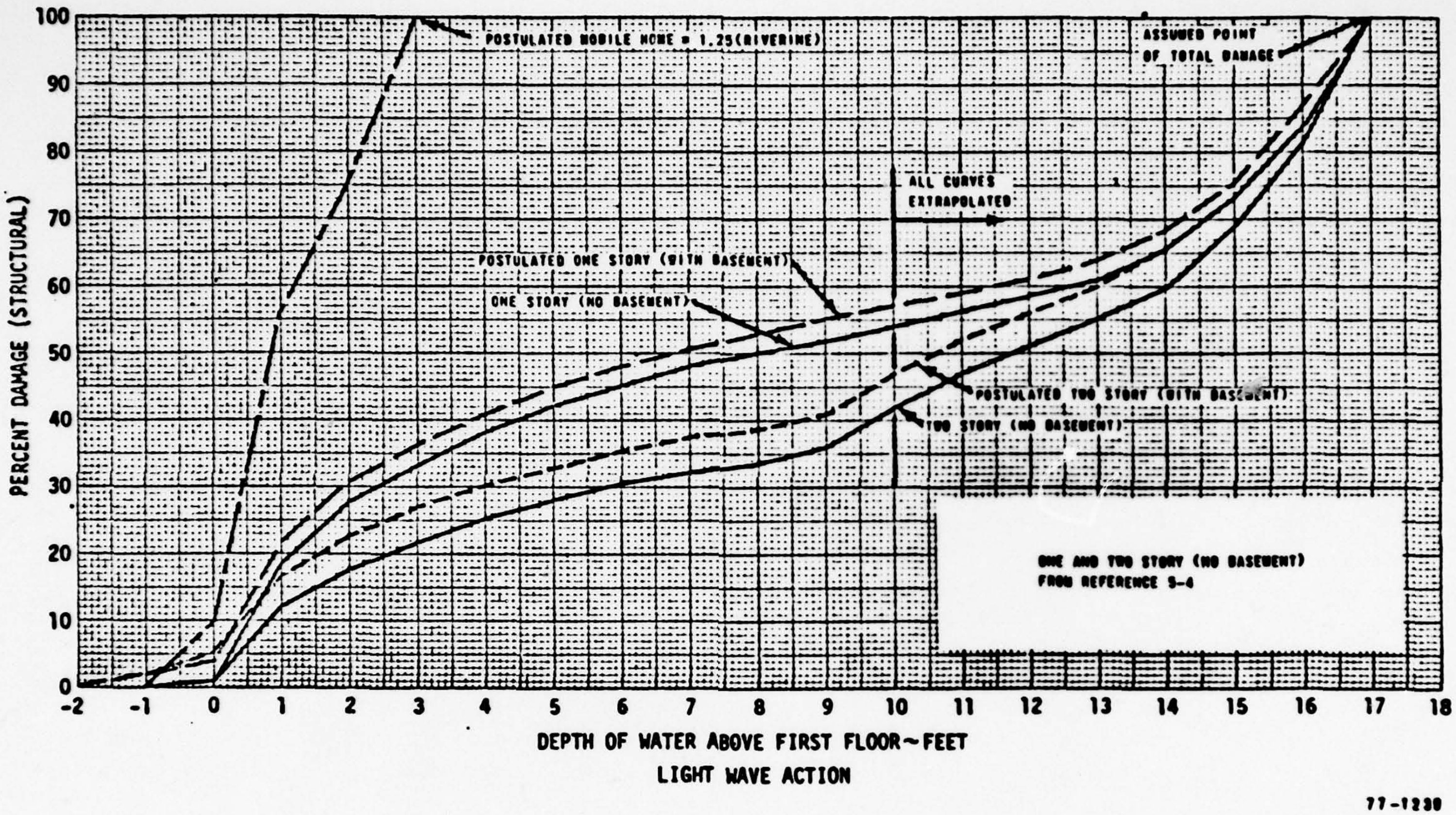

Figure 5-6b. Depth-Damage Curves (Storm Surge) for Structures

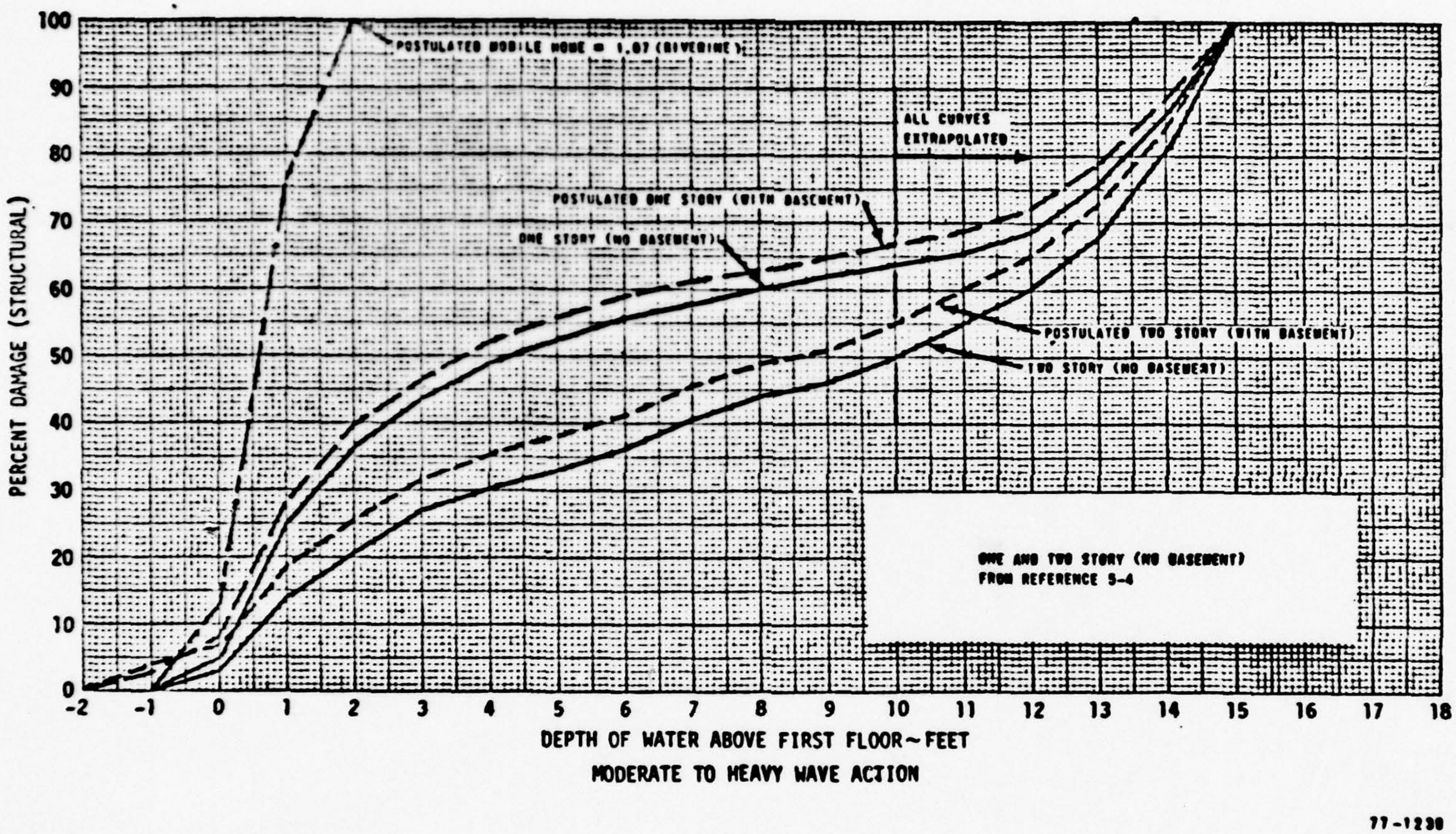

Figure 5-6c. Depth-Damage Curves (Storm Surge) for Structures

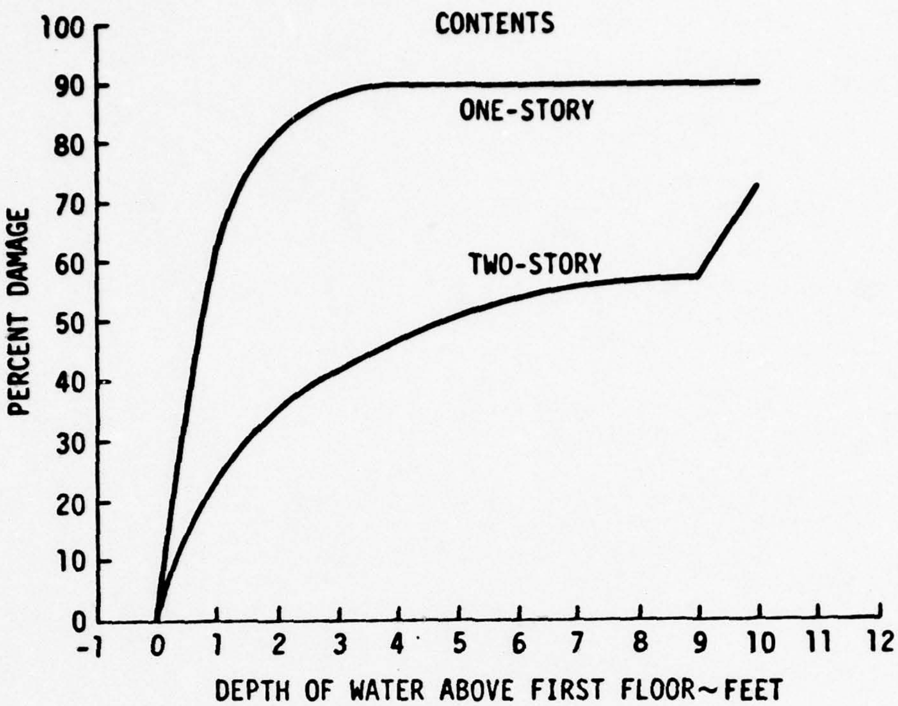

Figure 5-7a. Depth-Damage Curves (Storm Surge) for Residential Contents

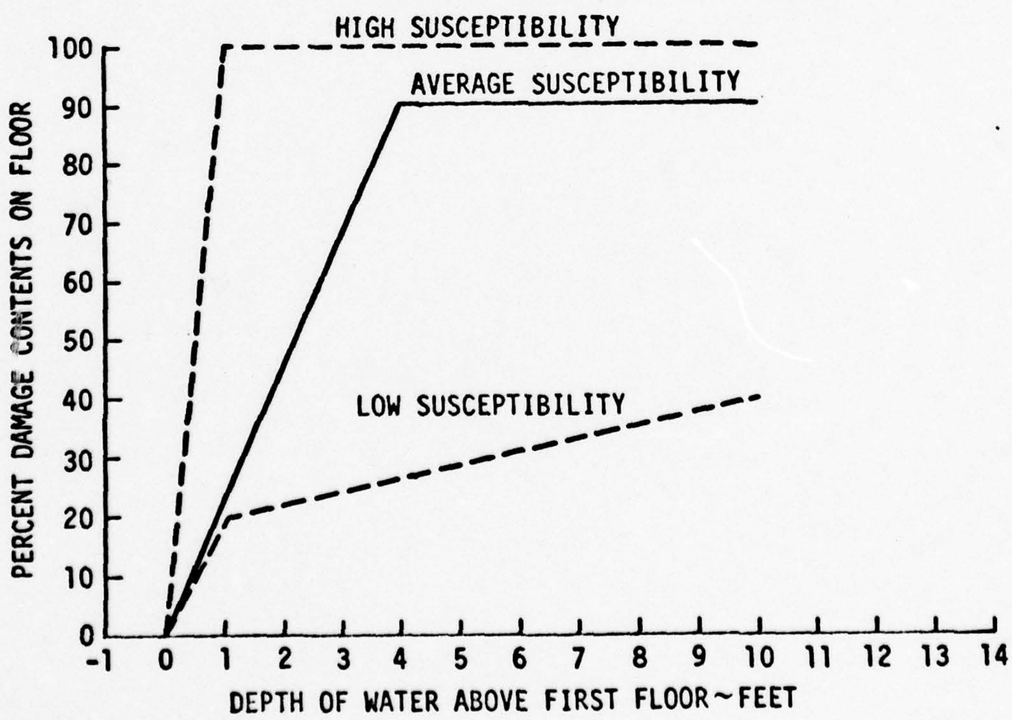

Figure 5-7b. Depth-Damage Curves (Storm Surge) for Non-Residential Contents - Postulated

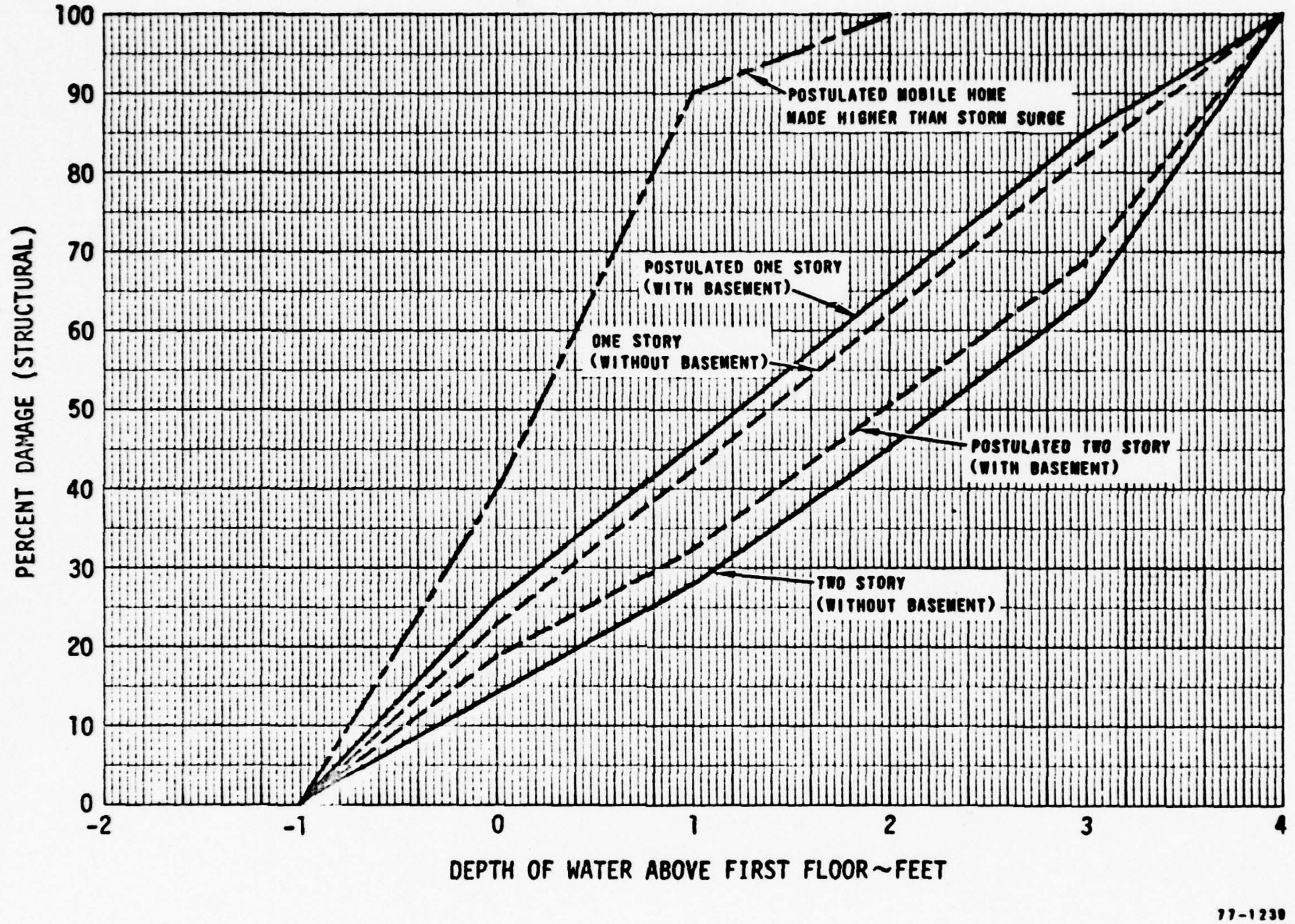

Figure 5-8. Depth-Damage Curves (Tsunami) for Structures and Contents

- Damage curves for one- and two-story residential structures with basements and mobile homes were postulated on the basis of 1975 FIA data for riverine flooding. The approximate percent difference in damage between residential structures with and without basements shown by the FIA data was used for tsunami.
- Damage curves for one- and two-story non-residential structures with and without basements were assumed to be the same as those for residential structures.
- Use the same depth-damage curves for both structures and contents.

5.4 Expected Losses

5.4.1 Economic and Mission Losses

In Section 5.2, the procedure used to obtain the probabiltiy of experiencing various depths of water in a building was discussed. Section 5.3, in turn, related water depth to damage. Now, a procedure for calculating the expected annual average economic loss shall be outlined.

- Determine the probability of all possible flood intensities (i.e., flood depths) being experienced. Use one-foot increments as the step size and incorporate the first floor elevation (i.e., the hazard model).
- Determine the corresponding damage. Use the average depth (i.e., $\frac{h_a+h_b}{2}$) to select values from the appropriate damage algorithm (i.e., the damage algorithm).
- Obtain the total replacement value of the structure and its contents (i.e., the exposure model).
- Determine the vulnerability level of the structure's contents if it is a non-residential structure. This parameter will have been determined during the base inspection (Section 7).
- Determine the expected average annual economic loss using the following equation

$$E\langle LOSS\rangle = \sum_{g=1}^{3} \sum_{i=1}^{N} \lambda_{ig} \sum_{h=1}^{2} D_{ih} V_h \qquad (5\text{-}4)$$

where

g = index for type of flood

1 = riverine flooding (if applicable)
2 = storm surge (if applicable)
3 = tsunami (if applicable)

i = index for flood depths (above floor)

1 = 0 to 1 foot
2 = 1 to 2 feet
etc.

h = index for type of damage

1 = structure
2 = contents

N = number of flood depths (varies from building to building)

λ_{ig} = depth rate (Hazard Model)

= P_{ig}, the depth probability as determined by Equation 5-3*

D_{ih} = ratio of repair cost to total replacement cost, depends on vulnerability and structure use (Damage Algorithm)

= damage percentage ÷ 100

V_h = value exposed (Exposure Model)

The determination of mission reliability (see Section 6.1) requires knowledge of the reliability of each structure in the mission network. The building reliability (i.e., the probability that the building will remain functional throughout the year) is calculated using Equation 5-5. Just as with the other hazards, a damage level of 20 percent was

*For a Poisson Process the probability of occurrence during a short time Δt is equal to $\lambda\Delta t$. The probability P_{ig} as determined by equation 5-3 is the probability of occurence in 1 year. If we let Δt = 1 year, then $P_{ig} = \lambda_{ig}\Delta t = \lambda_{ig}$. This approximation is valid only when 1 year is small compared to the return period, $1/\lambda$.

selected as the critical cutoff. Above 20 percent damage, the building is assumed to be non-functional; below 20 percent, the building is assumed to be functional. In addition, both damage to the structure and contents are considered. If damage to either exceeds 20 percent, the building is assumed to be non-functional.

Note however, that not all buildings will appear in the mission network. Consequently, many of the structures that receive more than 20 percent damage will be important from the standpoint of economic loss but not for mission reliability.

$$\begin{aligned} \text{RELIABILITY*} &= 1 - \text{Probability (failure)} \\ &= 1 - \prod_{i=1}^{3} (1 - P_i) \\ &= 1 - (P_1 + P_2 + P_3 - P_1P_2 \\ &\quad - P_2P_3 - P_2P_3 + P_1P_2P_3) \end{aligned} \tag{5-5}$$

where

$$P_1 = \text{Probability (failure due to riverine flooding)} = \sum_{i=M}^{N} P_{i1}$$

$$P_2 = \text{Probability (failure due to storm surge)} = \sum_{i=M}^{N} P_{i2}$$

$$P_3 = \text{Probability (failure due to tsunami)} = \sum_{i=M}^{N} P_{i3}$$

*Of a single structure.

M = lowest flood depth index for which damage exceeds 20 percent (will depend on vulnerabiltiy and structure use)

The occurrence of one flood hazard has been assumed to be independent of the occurrence of the others. Again failure is defined as having more than 20 percent damage.

5.4.2 Personnel Losses

There is no question that flooding, be it riverine, storm surge, or tsunami, often causes a significant number of casualties. During the period from 1955 through 1969, the average annual life loss from riverine flooding alone was 83. As with the hazards already discussed, however, no data exists on the effect of structural floodproofing or other mitigations on the casualty rate or even the casualty rate itself. It does appear that the primary elements which affect the casualty rate are

- the warning system, and
- the evacuation system.

These elements are well beyond the scope of this project. For these reasons, it is not possible to develop a mitigation program for flooding based on reducing the risk of death and injury.

5.5 Methodology

The initial input needed for flood is basically the same as that requred by all hazards. It consists of six types: hazard and damage, exposure and vulnerability, and mitigation and cost. Much of this information is provided by the base inspection-form for flood (Section 7).

5.5.1 Structures

The methodology (Figure 5-9) beings by inputing the structure's identification number, the elevation of the first floor, and the type of flood to which the structure is vulnerable. Additional data, shown being received from the side, is comprised of that which is used by all structures. It includes probability/depth relationships and depth/damage curves for riverine, storm surge, and tsunami flooding. Cost factors are also needed to estimate the cost of the mitigations.

Once the required input has been provided to the methodology, the next step is to determine whether or not the structure is in a floodplain. If it is not, there exists no hazard from flooding and therefore, flood is not considered in any subsequent analysis. However, if the structure is vulnerable to some type of flooding, all applicable flood mitigations m must be considered to select that one which is best in terms of benefit/cost. Assume that the structure is within a flood plain. The next step is to determine whether or not the building contains a basement. This is important because the types of mitigations applicable depend on the existence or nonexistence of a basement. For instance, a viable mitigation for structures without basements might be to elevate the structure.

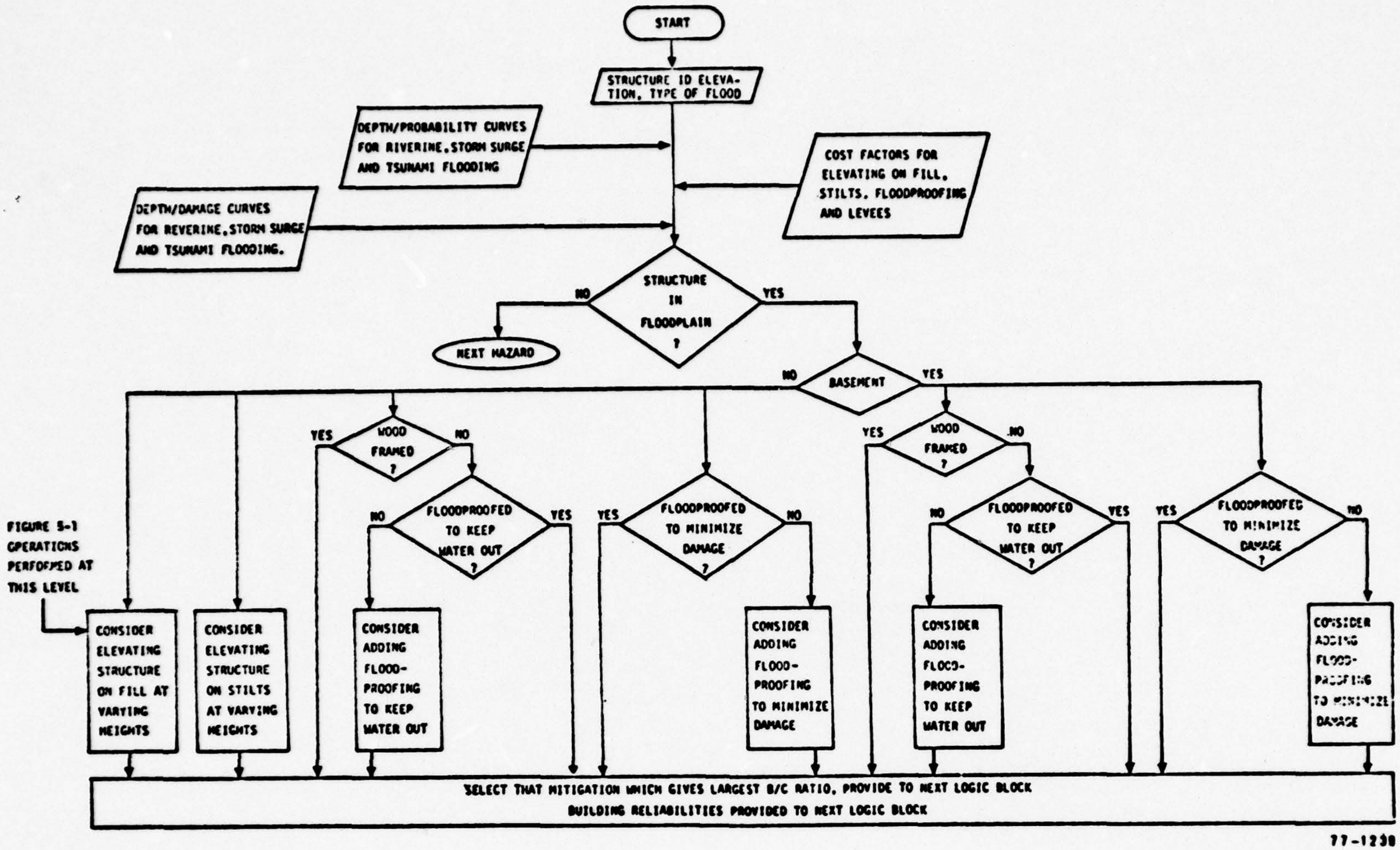

Figure 5-9. Flood Hazard

This mitigation is not practical for structures with basements since the cost of modifying the foundation would be too great. In this case only mitigations such as flood proofing would be considered.

Two types of flood proofing are defined, flood proofing to keep water out and flood proofing to minimize damage. Flood proofing to keep water out defines those mitigations which impede the passage of water and eject seepage. Basically this mitigation includes the permanent closure of un-needed wall openings and the installation of sump pumps. However, residential construction does not lend itself to this type of flood proofing because of extensive use of material which will not impede the passage of water. As a result, the structure is checked for construction type (i.e., wood framed). If it is wood framed, flood proofing to keep water out is not considered. The effect of this migitation on the damage algorithm is described as follows:

- Water level below height of flood proofing - no damage
- Water level above height of flood proofing - damage same as it would be with out flood proofing

Flood proofing to minimize damage defines those mitigations which permit the entrance of water but minimize the expected damage using non-structural modifications. These mitigations include proper anchoring, water resistant paints, adequate drainage, etc. The effect of this mitigation is to reduce the damage by 50 percent.

Therefore, for structures that contain basements, two mitigations exist:

- Flood proofing to keep water out
- Flood proofing to minimize damage

Flood proofing to keep water out is only applied to non-wood structures.

If the structure does not contain a basement, four possible mitigations exist. These are:

- Elevating the structure on fill (check various heights)
- Elevating the structure on stilts (check various heights)
- Flood proofing to keep water out
- Flood proofing to minimize damage

In mitigating the flood hazard by elevating the structure, we must consider the effects at varying heights. By performing a benefit/cost analysis at each height, the most optimal elevation in terms of flood resistance is obtained. This iterating process at varying heights applies to both methods of elevation (i.e., elevating on fill or stilts). The maximum elevation increase considered is 6 feet.

In considering flood proofing measures, the two types previously discussed for structures with basements are also applicable here. Again, flood proofing to keep water out is applied only to non-wood structures.

In considering the different mitigations, all relevant flood hazards must be considered. That is, if a particular facility is vulnerable to all three types of flooding, the expected reduction in damage due to a mitigation must be calculated for all three types. These reductions in damage or increases in reliability are then combined and divided by the cost of the mitigation to obtain the benefit/cost ratio. These ratios are used to determine which mitigation is to be added.

At this point, the best mitigation for each building, as well as the original reliability, is sent to the next logic block (see Section 1.4 and 6).

5.5.2 Mitigations

Flood damage mitigation embraces all methods for combatting the effects of excess water. This broad definition encompasses measures of which many were not considered. The commonly accepted measures are as follows:

Included Explicitly in this Methodology

- Elevate structure on fill or stilts
- Floodproofing a specific structure to keep the water out (assumed to reduce damage to zero, exclude wood structures)
- Floodproofing a specific structure to minimize damage

Included Implicitly in this Methodology

- Control of flood plain useage (keep sensitive structure out of the flood plain)

Not Included in this Methodology

- Reduction of peak flow by reservoirs (also called protection by structural measures)
- Confinement of the flow within a predetermined channel by levees or flood walls (also called protection by structural measures)
- Reduction of peak stage by increased velocities resulting from channel improvement (also called protection by structural measures)

- Diversion of flood waters through bypasses or floodways
- Temporary evacuation of the flood plain (requires forecasting and warning systems)
- Reduction of flood runoff by land management (also called flood abatement)
- Flood insurance (spreads the losses over many years and to many people)

The first three measures are considered explicitly by the proposed methodology as shown by the flow chart (Figure 5-9). The fourth measure has not been considered herein, but may be evaluated by the user through his control of input data. The remaining measures are available to the Navy and often have been utilized by them. For instance, Reference 5-7 gives a detailed plan for emergency evacuation of personnel at the Parris Island MCRD. However, these measures are not adaptable to the present methodology which considers each structure separately.

5.6 Availablity and Adequacy of Data

The first requirement for evaluating the flood hazard is that a stage-frequency or depth-probability curve be available for any flood plains affecting the subject facility. For the demonstration facility, the Marine Corps Recruit Depot at Parris Island, this inforamtion is available from the base master plan [5-2]. Whether or not this data exists for all facilities, especially those in foreign contries, is not known at this time. Agencies which may have this information for domestic facilities, if it is not in the base master plan, are:

- Army Corps of Engineers (CE)
- National Oceanic and Atmospheric Administration (NOAA)
- Soil Conservation Service (SCS)
- Geological Survey, (USGS), or the
- Local Flood Control District

An area of uncertainty with respect to this information is its accuracy. This is dramatically illustrated by Figure 5-10 which shows two depth-probability curves for the MCRD at

Parris Island. Both were taken from Reference 5-2; one curve was produced by Army Corps of Engineers and the other by NOAA. At the 10 foot depth, there is a factor of three difference in probability of occurrence.

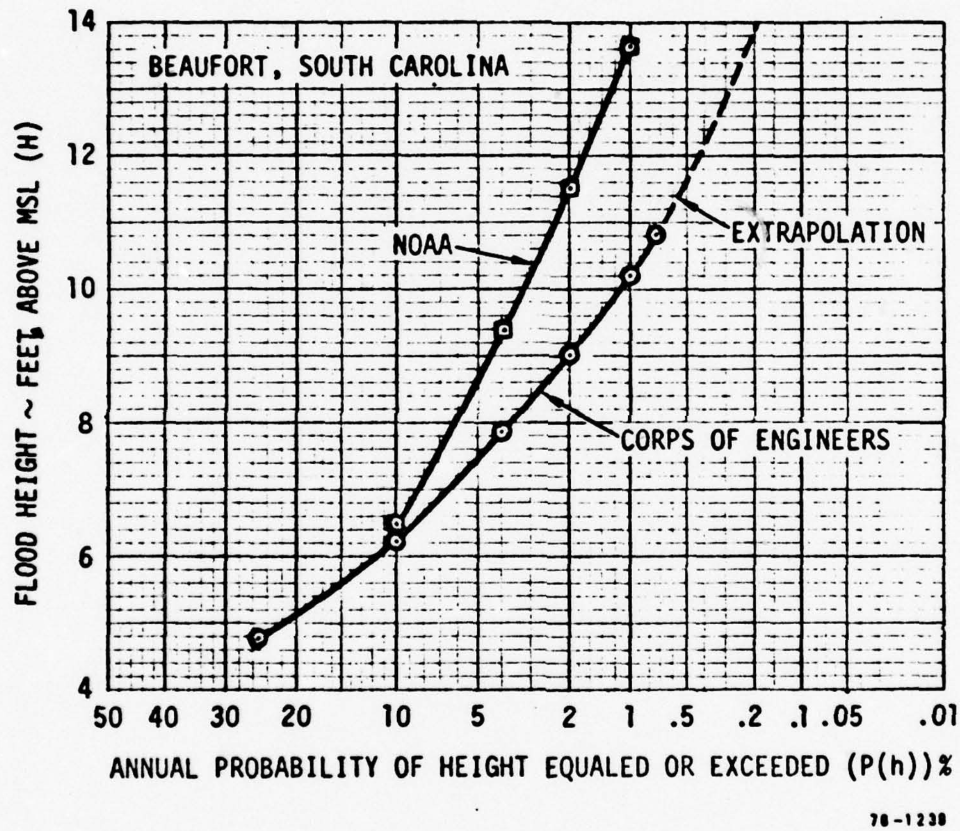

Figure 5-10. Depth-Probability Data for MCRD at Parris Island

Which of the two provides the best estimate is not known, although the NOAA curve has been selected for use in the example. During the recent past there have been three government agencies particularly concerned with flood probabilities: CE, NOAA, and USGS. All three developed their own techniques for generating state-frequency (i.e., depth-probability). In addition, the depth-probability relationship may be synthetic or analytic. For example, a synthetic storm surge relationship is generated by taking probabilistic hurricane parameters, inserting them into a deterministic storm surge computer program (SPLASH, for example [5-6]), and calculating the depth-probability relation. The analytic approach on the other hand uses the historical record of experienced stages together with an assumed frequency distribution, (the log Pearson Type III distribution, for example [5-11]) to produce the depth-probability relation. So the techniques used are many, and the results varied.

Another important parameter is the depth-damage relationship. Flood damages are calculated with the use of depth of flooding versus percent damages curves as shown in Figures 5-4, 5-5, 5-6, 5-7, and 5-8. Several government organizations have compiled data of this type [5-9] including the Federal Insurance Administration (FIA), the Army Corps of Engineers (CE), the Soil Conservation Service (SCS), and the Tennessee Valley Authority (TVA). Grigg [5-8] feels that the current FIA curves are the most applicable data for residential structures because the FIA has made a specific effort to generalize a great deal of data. Consequently the 1975 FIA curves [5-3] for residential and small business structures were selected for this methodology. Generalized curves for commerical and

industrial areas which would be representative of non-residential Navy buildings do not currently exist [5-9]. The development of better depth-damage curves for residential and especially non-residential structures and contents is very much needed.

Although the FIA damage curves for inland flooding are widely used, the storm surge relationships presented here are not. They were based on curves developed by the New Orleans District of the Corps of Engineers [5-4]. Although most of the CE coastal districts have procedures for determining storm surge damage, these procedures are usually not presented in a form that can be applied to other localities.

Flooding damage is affected by many variables other than depth of flooding. Duration of flooding, silt content, degree of alkalinity or salinity, flow velocity and the type of construction are a few of the important varibles. Because these parameters vary from locale to locale, "average" curves such as those developed by the FIA will not apply to every location. The storm surge curves, on the other hand, were developed for a particular locale. Consequently, they may be in error when applied to another area.

5.7 Definitions for Flood Hazard

Abatement - flood-damage mitigation by regulating the runoff of water into tributary streams and by controlling erosion.

Channel - a natural or artificial watercourse of perceptible extent, with a definite bed and banks to confine and conduct continuously or periodically flowing water. Channel flow thus is that water which is flowing within the limits of the defined channel.

Drainage - systems for dealing with excess water. The three primary drainage tasks are urban storm drainage, land drainage, and highway drainage. Except for highway culverts and bridges, drainage deals with water before it has reached major stream channels.

Flood - an overflow of lands not normally covered by water; a temporary increase in streamflow or stage; or the discharge causing the overflow or temporary increases.

Flood-Damage Mitigation - methods for combatting the effects of excess water; often called "flood control," but this term should only be used for the "structural measures - dams, etc."

Flood Frequency - an expression of how often a flood of given magnitude can be expected. (Note: the word "frequency" often is omitted to avoid monotonous repetition.) Examples:

> 10-Year Flood or 10-Year-Frequency Flood - the flood which can be expected to be equaled or exceeded on an average once in 10 years and which would have a 10-percent chance of being equaled or exceeded in any given year.

50-Year Flood - ... two-percent chance ... in any given year.
100-Year Flood - ... one-percent chance ... in any given year.
500-Year Flood - ... two-tenths-percent chance ... in any given year.

Flood Fringe - that portion of the flood plain outside the floodway.

Flood Peak or Peak Discharge - the highest stage or discharge attained during a flood.

Flood Plain - the land adjacent to a body of water which has been or may be hereafter covered by flood water including but not limited to the regulatory flood.

Flood Plain Regulation - flood-damage mitigation through ordinances to control construction and development of flood plains.

Flood Probability - the chance that a flood of a given return frequency will occur during any one year.

Flood Proofing - a combination of structural provisions, changes, or adjustments to properties and structures subject to flooding primarily for the reduction or elimination of flood damages. Two types of flood proofing exist: 1) flood proofing to keep water out of the building and 2) flood proofing to minimize damage although water is allowed into the building.

Floodway - the channel of a stream and those portions of the flood plain adjoining the channel that are required to carry and discharge the flood water of flood flows of any river or stream including but not limited to flood flows associated with the regulatory flood.

Frequency-Discharge Curve - a plotted line showing frequency of various flood discharges at a surveyed cross section or other point along a stream (used with a stage discharge curve to determine the high-water elevations resulting from selected flood discharges at that point on the stream).

Hydrograph - a plotted curve showing the rise and fall of stream flow with respect to time at a specific point on a stream.

Hydrologic Cycle - the process involved in the transfer of moisture from the sea to the land and back to the sea again.

Hydrology - the science of dealing with the waters of the earth; their occurrence, circulation, and distribution; their chemical and physical properties; and their reaction with their environment.

Precipitation - the water which falls from the atmosphere to the earth's surface; among the various forms of precipitation are rain, snow, hail, sleet, fog drip, and dew.

Protection by Structural Means - flood-damage mitigation through the construction of engineering works to control or protect against flood waters.

Recurrence Interval - the average interval in years between the occurrence of a flood equal to or greater than a specified magnitude (also called Return Period).

Runoff - that portion of the total storm rainfal flowing across the ground or other surface and contributing to the flood discharge.

Stage-Discharge Curve - a plotted curve showing elevations resulting from a range of discharges at a surveyed cross section, stream gage, or other point on a stream.

Stage-Frequency Relationship - a curve or equation relating the return frequency to flood height (also see Flood Frequency).

5.8 Reference for Flood Hazard

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6. INVESTMENT PROGRAMS FOR EACH HAZARD

6.1 Mission Impairment

6.1.1 Introduction

The flowchart, Figure 6-1, explains the methodology used in assessing mission reliability. It introduces the concept of a reliability network, explains the iterative process by which an acceptable level of reliability is reached, and defines the benefit/cost analysis used to obtain the best mitigations. Note that the methodology developed herein is only part of the general methodology described in Section 1.2. Where Section 1.2 describes in general the process by which an optimum capital investment program would be reached to mitigate the risks of all hazards, this section details the process for mission reliability and economic loss.

The methodology initially requires the acquisition of certain data. These include a list of the structures that comprise the mission. In addition, the role and uniqueness of role of each structure within the mission must be established. Also required as additional data are the initial reliabilities of the structures and the best mitigation for each structure/hazard combination. These mitigations are those output from the individual hazard methodologies (Sections 2 through 5). Finally, the desired mission reliability must be specified. This reliability is that level of risk which has been decreed to be acceptable (for example, the Navy might require a 99.9 percent probability that the mission remains functional) due to exposure to each hazard separately.

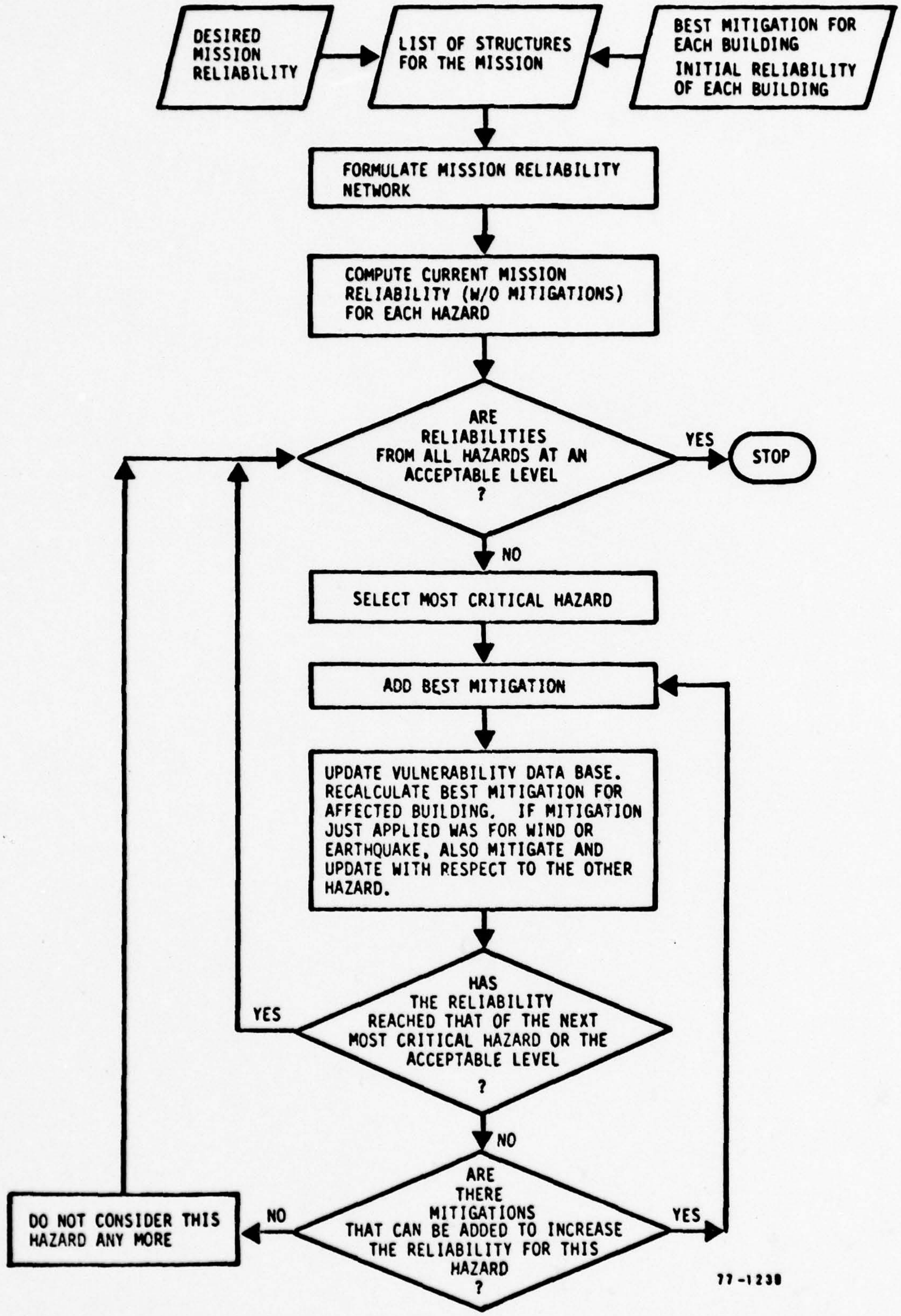


Figure 6-1. Mission Reliability

The sequence described here is not necessarily optimum from the standpoint of total mission reliability as it was defined in Section 1.6. Instead, it concentrates on balancing the risk due to each hazard separately. See Section 1.6 for a detailed discussion of the differences between an "optimum capital investment program" and one providing "equal level of protection" from each hazard.

The proposed methodology provides a capital investment program based on maximizing the benefit/cost ratio. That is, a list of structures and mitigations ranked in order of decreasing benefit/cost ratios is presented.

6.1.2 Mission Network

To construct a mission network, the role and uniqueness of role of each structure must be established. In doing this, we would also like to establish the existence of backup capabilities.

Figure 6-2 shows a possible mission and its component structures. Each of these structures has four initial probabilities, defined as P_{ij}, where

i indicates the structure number

j indicates the hazard
1 = fire
2 = wind
3 = earthquake
4 = flood

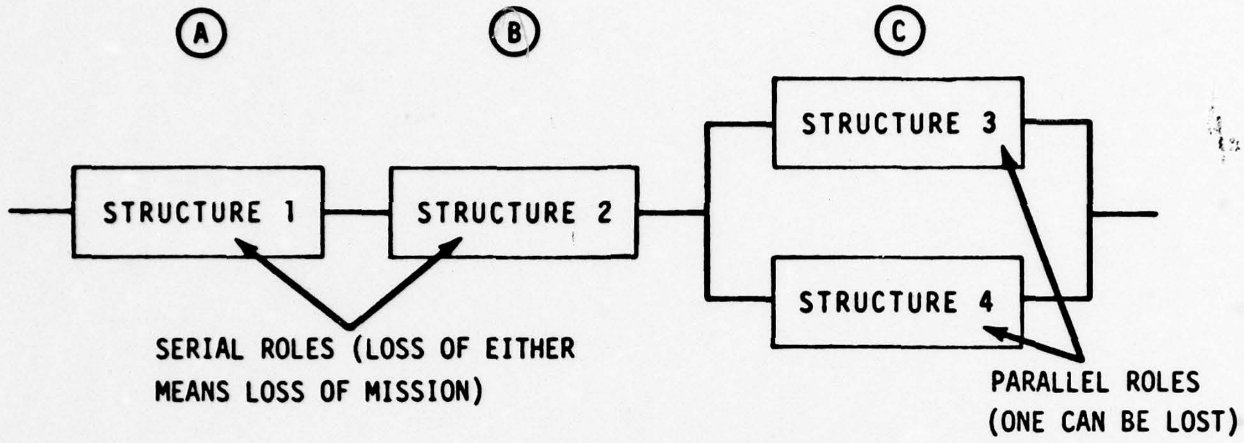


Figure 6-2. Mission-Network (Example 1)

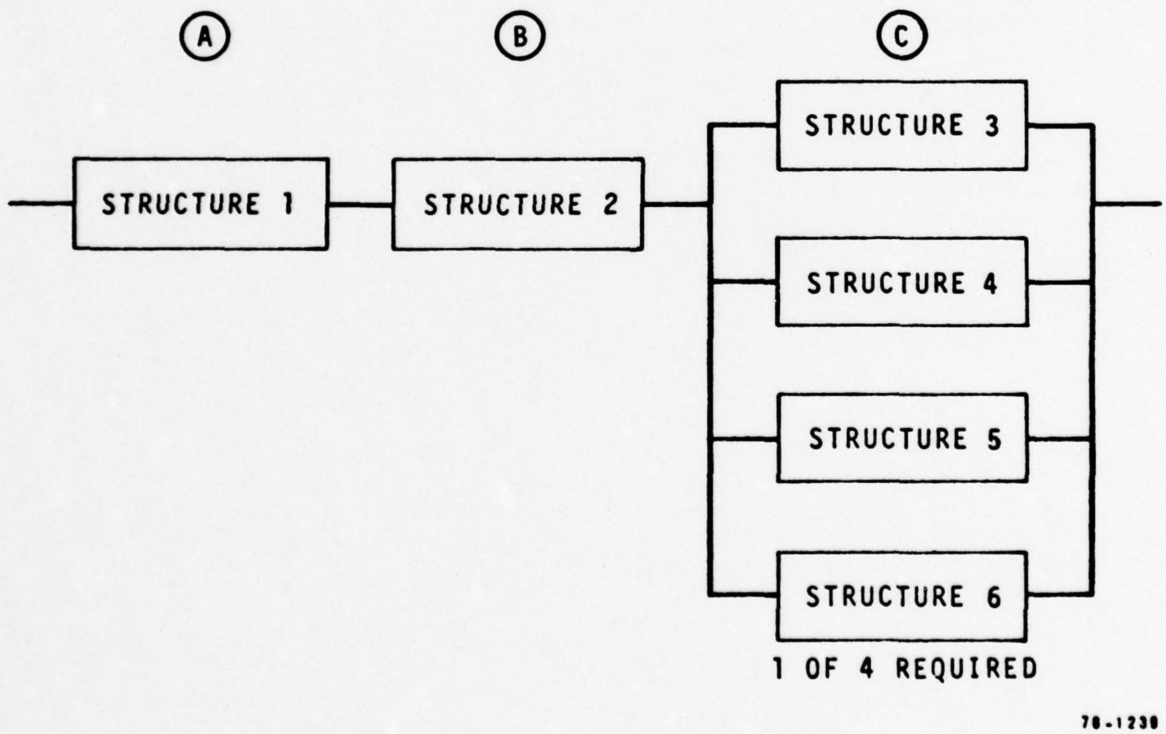


Figure 6-3. Mission Network (Example 2)

P_{ij} represents the probability of failure and when subtracted from 1 represents the reliability of the structure. The analysis which follows herein will utilize this relationship. That is,

$$R_{ij} = 1 - P_{ij} \qquad (6\text{-}1)$$

where R_{ij} is the reliability.

The mission network, as represented by Figure 6-2, is analogous to the networks used in electrical circuit theory. Referring to Figure 6-2, there are two ways that structures enter into the mission: in parallel or in series.

Structures 1 and 2 are in series. That is, the functional operation of the system depends on the proper operation of both.

Structures 3 and 4 are in parallel. The functional operation of this system depends only on the proper operation of one or the other. Notice, however, that the 3-4 combination is in series with 1 and 2. Structures 3 and 4 are redundant structures. Each provides backup capability for the other. If both were required for the mission, they would not be modeled as parallel elements, but rather as series elements. A more complex use of parallel elements is to have several structures in parallel but requiring more than one be operational (Figure 6-3). The computer program as presently constituted, only handles the case where only one building out of a parallel system is required for system operation.

Although the network possesses an apparent sequential property, this property is not strict. That is, the formulation is

arbitrary. It is only important that the relative locations of the parallel and series elements remain stationary.

6.1.3 Mission Reliability

To calculate the mission reliability, F, we again resort to the methods and tools of circuit theory. We will first compute the probability of failure of the system, P, and then use equation 6-1 to obtain R.

Let $\overline{P}_\alpha$ be the probability of failure of each element in series. For the examples shown in Figures 6-2 and 6-3:

$\overline{P}_A$ = probability of failure of structure 1 = P_{1j}

$\overline{P}_B$ = probability of failure of structure 2 = P_{2j}

$\overline{P}_C$ = net probability of failure of the parallel elements.

Let,

$$P = \text{probability of failure of the total system}$$

$$= P[(A \text{ fails}) \cup (B \text{ fails}) \cup (C \text{ fails})]$$

$$= \overline{P}_A + \overline{P}_B + \overline{P}_C - \overline{P}_A\overline{P}_B - \overline{P}_A\overline{P}_C - \overline{P}_A\overline{P}_B + \overline{P}_A\overline{P}_B\overline{P}_C \quad (6\text{-}2)$$

For the general case, the probability of failure for a system in series is given by

$$P = 1 - \prod_{\alpha=1}^{n} (1 - \overline{P}_\alpha) \quad (6\text{-}3)$$

where,

α = index of each series block*

n = total number of series structures and sets of structures.

*The alaphabetic subscripts used in equation (6-2) have been switched to numeric subsripts for convenience.

For the block of structures in parallel (Block C in Figures 6-2 and 6-3), the net probability of failure is given by

$$P_\alpha = \text{probability [All the structures in the block fail]}$$

For the Figure 6-2 example,

$$\bar{P}_\alpha = \bar{P}_C = P[(3 \text{ fails}) \cap (4 \text{ fails})] \qquad (6\text{-}4)$$

$$= P_{3j} + P_{4j}$$

For the Figure 6-3 example,

$$\bar{P}_\alpha = \bar{P}_C = P[\text{at least three out of the four fail}]$$

For the general case, the probability of failure of a block of parallel structures is given by the following equation.

$$\bar{P}_\alpha = \prod_{i=1}^{n} P_{nj} \qquad (6\text{-}5)$$

The probability of failure of the total system shown in Figure 6-2 is now obtained by evaluating equation 6-5 for $\bar{P}_C$ and inserting that result into equation 6-3. Thus, the system failure, P, in terms of the building failure probabilities, P_{ij}, is

$$P = P_{1j} + P_{2j} + P_C - P_{1j}P_{2j} - P_{1j}P_C - P_{2j}P_C + P_{1j}P_{2j}P_C \qquad (6\text{-}6)$$

where,

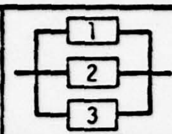
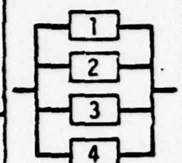
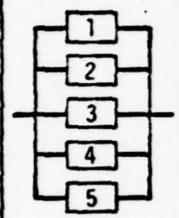
$$P_C = P_{3j}P_{4j}$$

The system reliability, R, is finally computed by utilizing equation 6-1. That is,

$$R = \text{Reliability of the total system}$$
$$= 1 - P$$

When several structures are required to be functional from a parallel set, the relationship is more complex. Six combinations are shown in Figure 6-4. Chapter 8 of Reference 6-2 provides the basic methodology used to develop these relationships.

This model currenlty assumes statistical independence of structural failures (losses) which is valid for fire but questionable for flood, wind and earthquake. However, Panoussis [6-1] has shown that this assumption is a conservative one. Some further study of the influence of statistical correlation will be required before this model is put into general use.

TWO-OUT-OF-THREE SYSTEM		$P_1P_2 + P_1P_3 + P_2P_3 - 2P_1P_2P_3$
TWO-OUT-OF-FOUR SYSTEM		$P_1P_2 + P_1P_4 + P_3P_4 + P_1P_3 + P_2P_4 + P_2P_3 - 2P_1P_2P_4$ $- 2P_1P_3P_4 - 2P_1P_2P_3 - 2P_2P_3P_4 + 3P_1P_2P_3P_4$
THREE-OUT-OF-FOUR SYSTEM		$P_1P_2P_3 + P_1P_2P_4 + P_1P_3P_4 + P_2P_3P_4 - 3P_1P_2P_3P_4$
TWO-OUT-OF-FIVE SYSTEM		$P_1P_2 + P_2P_3 + P_3P_4 + P_4P_5 + P_1P_3 + P_2P_4 + P_3P_5 + P_1P_4$ $+ P_2P_5 + P_1P_5 - 2P_1P_2P_3 - 2P_2P_3P_4 - 2P_2P_3P_5 - 2P_1P_3P_4$ $- 2P_2P_4P_5 - 2P_3P_4P_5 - 2P_1P_2P_4 - 2P_1P_3P_5 - 2P_1P_4P_5 - 2P_1P_2P_5$ $+ 3P_1P_2P_3P_4 + 3P_2P_3P_4P_5 + 3P_1P_2P_3P_5 + 3P_1P_3P_4P_5 + 3P_1P_2P_4P_5 - 4P_1P_2P_3P_4P_5$
THREE-OUT-OF-FIVE SYSTEM		$P_1P_2P_3 + P_1P_2P_5 + P_1P_4P_5 + P_3P_4P_5 + P_1P_2P_4$ $+ P_1P_3P_5 + P_1P_3P_4 + P_2P_4P_5 + P_2P_3P_5 + P_2P_3P_5 + P_2P_3P_4$ $- 3P_1P_2P_3P_5 - 3P_1P_2P_4P_5 - 3P_1P_3P_4P_5 - 3P_1P_2P_3P_4$ $- 3P_2P_3P_4P_5 + 6P_1P_2P_3P_4P_5$
FOUR-OUT-OF-FIVE SYSTEM		$P_1P_2P_3P_4 + P_1P_2P_3P_5 + P_1P_2P_4P_5 + P_1P_3P_4P_5$ $+ P_2P_3P_4P_5 - 4P_1P_2P_3P_4P_5$

78-1230

Figure 6-4. Reliability of k-out-of-n Parallel Systems

6.2 Economic Loss

The flowchart in Figure 6-5 explains the methodology used in assessing economic loss. It is only part of the general methodology discussed in Section 1-2. It follows many of the concepts originally introduced for mission reliability.

The input data needed to perform the methodology includes 1) a list of all structures on the base, 2) the best mitigation for each building, and 3) an initial damage estimate for each building. Basically, this information is provided by the individual hazard methodologies of Sections 2 through 5. One last piece of information must be provided; a desired level of acceptability for expected damage. This value represents that level of economic loss which has been deemed to be acceptable (i.e., an expected economic loss of no more than XXX number of dollars is acceptable). Once this information has been entered, an optimum capital investment program based on decreasing benefit/cost ratios can be computed.

The initial damage estimates for the base, D_j^I, are calculated by summing over the individual building estimates for each hazard. That is,

$$D_j^I = \prod_{n=1}^{n} D_{ij}$$

where,

D_{ij} = average annual loss to building i from hazard j (w/o investigations)

i = structure index

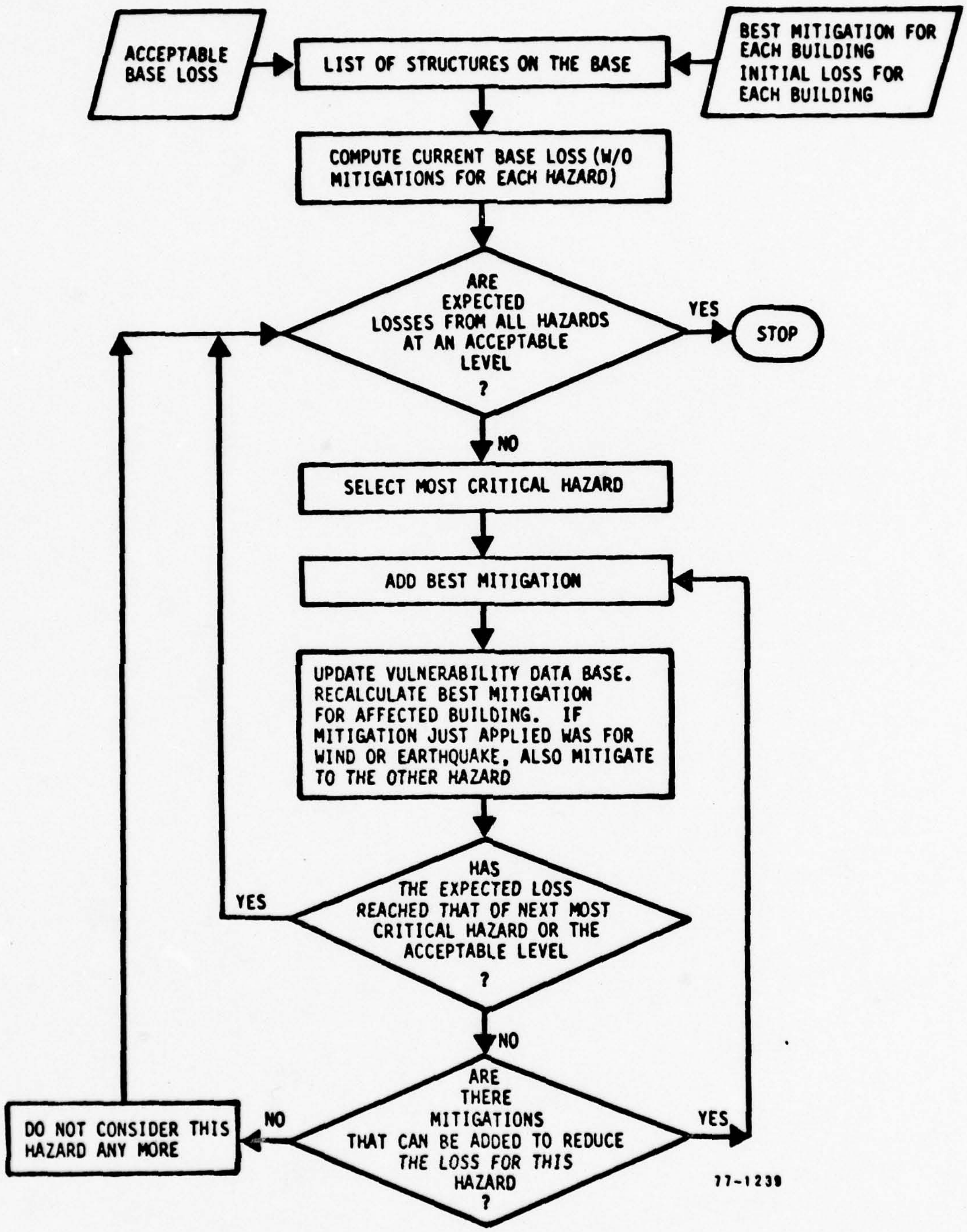


Figure 6-5. Economic Loss

j = hazard index

1 = fire

2 = earthquake

3 = wind

4 = flood

n = total number of structures on the base

The next step is to examine each of the building/mitigation alternatives to determine which possesses the largest benefit/cost ratio. That alternative which provides the largest reduction in damage for the money spent is then selected. The corresponding reduction in damage is then subtracted from the original amount, D_j^I, and the new expected base damage set to D_j^N.

D_j^N is then checked to see if it is less than or equal to that of the next critical hazard or the acceptable level. If it is, the analysis terminates, and returns back to examine if all hazards are acceptable. If D_j^N is not acceptable, the modified building is flagged, the new expected damage is set to D_j^N, and another building/mitigation is selected. This iterative process continues until the total expected damage for the base becomes acceptable or until all of the possible mitigations have been added. At this point the analysis stops, unless the effect of uncertainty is being considered. In that case, the analysis is repeated several times using perturbed damage algorithms (See Section 9 for details).

7. INSPECTION FORMS

7.1 Base Information Form

The base information form is used to record data of a general nature. Among other things, it identifies the base, it locates the base with respect to latitude and longitude, and it gives the date of the inspection. A copy of the form is provided in Figure 7-1. Only one base inspection form needs to be completed for the activity being evaluated.

7.2 Building Inspection Form

The Building Inspection Form contains information on the vulnerability, exposure, and cost of a building. It is used to provide the necessary input to the general and individual-hazard methodologies. The form, itself, should be completed by an engineer or building inspector familiar with evaluating buildings since much of the information is based on professional opinion and judgement. The form together with instructions for completing it are given in Appendix C. A copy of the form is also provided in Figure 7-2. The form is made up of six sections:

- General information
- Fire risk data
- Flood risk data
- Earthquake risk data
- Wind risk data
- Comments
- Engineer code number

One form must be provided for each building being evaluated.

BASE INFORMATION FORM (TWO PAGES)

A. ACTIVITY NAME (1 CARD)

1 … 60

B. CHAIN OF COMMAND (3 CARDS)

1 … 60

1 … 60

1 … 60

C. ACTIVITY LOCATION (1 CARD)

COUNTRY 1 … 20

STATE 21 … 40

COUNTY 41 … 60

LATITUDE - DEG. 61 … 69 NORTH ○ 70 SOUTH ○ 70

LONGITUDE - DEG. 71 … 79 EAST ○ 80 WEST ○ 80

78-1238

Figure 7-1a. Base Information Form

D. OTHER INFORMATION (1 CARD)

DATE OF INSPECTION 1 – 20

DISCOUNT RATE 21 – 30

BASE POPULATION

OFFICER 31 – 40

ENLISTED 41 – 50

CIVILIAN 51 – 60

DEPENDENTS RESIDING ON BASE 61 – 70

E. SPECIAL COMMENTS (3 CARDS)

1 – 80

1 – 80

1 – 80

78-12

Figure 7-1b. Base Information Form (cont.)

* STARRED ITEMS MUST BE COMPLETED

BUILDING INSPECTION FORM

RIGHT JUSTIFY ALL ENTRIES

General Information

- *STRUCTURE IDENTIFICATION
- YEAR BUILT
- ORIGINAL COST
- REPLACEMENT COST
- *TOTAL FLOOR AREA
- AREA OF GROUND FLOOR
- NUMBER OF OCCUPANTS
- NO. STORIES ABOVE GROUND LEVEL
- BASEMENT (Y,N)
- NAVAL CATEGORY CODE
- *TYPE OF LOAD RESISTING SYSTEM
- TYPE OF FLOOR CONSTRUCTION
- TYPE OF ROOF CONSTRUCTION
- *EXTERIOR WALL CONSTRUCTION
- INTERIOR WALL CONSTRUCTION
- YEAR OF INSPECTION

Fire Risk Data

- CONSTRUCTION TYPE (R,N,O,W)
- CURRENT PROTECTION (N,D,S,B)
- INTERIOR FINISH (N,C)
- FIRE LOAD (L,M,S)
- NO. OF FIRE AREAS
- FIRE FREQUENCY CODE
- RESIDENCE (Y,N)

WHEN KEYPUNCHING, DUPLICATE FIRST 7 COLUMNS OF CARD 1 ONTO CARD 2

Flood Risk Data

- FIRST FLOOR ELEVATION (FT.)
- ON FLOOD PLAIN (Y,N)
- FLOOD PROOFED - LOW DAMAGE (Y,N)
- FLOOD PROOFED - NO DAMAGE (Y,N)
- FLOOD TYPE (R,S,T)
- CONTENT VULNERABILITY (L,M,H)

Earthquake Risk Data

- DESIGN LEVEL (1,2,3,4,5,6,7)
- CEILINGS, LIGHT FIXTURES (A,F)

Earthquake Risk Data Continued

- QUALITY OF LOAD RESISTING SYSTEM
- QUALITY OF FLOOR, ROOF, BRACING
- QUALITY OF PARTITIONS
- SPECIAL HAZARDS
- PHYSICAL CONDITION OF BLDG
- CONTENT STABILITY
- CONTENT DELICACY
- CONTENT OVER HANG

Wind Risk Data

- DESIGN LEVEL
- WIND EXPOSURE (A,B,C)
- NO. OF WINDOWS (F,A,M)
- AIRBORNE-WATER-PROOFED (Y,N)
- MOBILE STRUCTURE ANCHORED (Y,N)

Miscellaneous

- VALUE OF CONTENTS
- COMMENTS
- ENGINEER CODE NO.

Figure 7-2. Building Inspection Form

The first information requested identifies the structure, its age, value, size, and other pertinent data. This is followed by five code numbers which describe the building's

- Load resisting system,
- Floor construction,
- Roof construction,
- Exterior wall construction, and
- Interior wall construction

in considerable detail. In fact the detail provided here (see Tables 7-1 through 7-5) is considerably greater than that required by the risk mitigation methodology. This is intentional. If detailed informaiton is acquired initially for a facility, the mitigation methodlolgy can be continually upgraded without having to resurvey the facilities each time the methodology is changed. The relationship between the building's detailed description (Tables 7-1 through 7-5) and the building's categories required by the present mitigation methodology is given in Table 7-6.

Following the building description, the Building Inspection From requests data relating to

- Fire risk,
- Flood risk,
- Earthquake risk, and
- Wind risk.

Included within the form is the exposure data potentially required by the methodology:

- Structure original cost,
- Structure replacement value,
- Value of contents, and
- Number of occupants.

Table 7-1. Vertical and Lateral Load Resisting Systems

CODE	MASONRY CONSTRUCTION
1	Load bearing walls of unreinforced hollow unit masonry
2	Load bearing walls of reinforced hollow unit masonry
3	Load bearing walls of unreinforced solid unit masonry or grouted masonry
4	Load bearing walls of reinforced solid unit masonry or grouted masonry
5	Load bearing walls of unreinforced cavity wall masonry
6	Load bearing walls of reinforced cavity wall masonry
7	Load bearing walls of stone masonry
	Partially reinforced masonry construction shall be considered as unreinforced masonry for the purposes of this classififcation.
	CONCRETE CONSTRUCTION
8	Load bearing walls of pre-cast reinforced concrete construction (typically, tilt-up walls)
9	Load bearing walls of reinforced poured-in-place concrete
10	Load bearing walls of unreinforced poured-in-place concrete
11	Poured-in-place reinforced concrete frame
12	Precast reinforced concrete frame
13	Precast prestressed concrete frame
14	Combination of a poured-in-place reinforced concrete frame with reinforced concrete load bearing walls (i.e., shear walls)
15	Poured-in-place post-tensional reinforced concrete frame
	STEEL OR METAL CONSTRUCTION
16	Structural steel space frame (AISC Type 1 - rigid frame)
17	Structural steel space frame (AISC Type 2 - simple frame)
18	Structural steel space frame (AISC Type 3 - semi-rigid frame)
19	Structural steel two-dimensional frame
20	Structural steel frame (type unknown)
21	Partial steel frame with reinforced concrete frame or load bearing walls
22	Light steel or other metal frame
	WOOD CONSTRUCTION
23	Wood frame (light timber)
24	Wood frame (heavy timber)
25	Wood frame (structurally glued - laminated timber)
26	Wood frame with stucco or lumber sheathing
	OTHER
27	Adobe
28	Mobile home
29	Unknown

Table 7-2. Floor Construction

As used here, the floor is that part of the building's structure which transfers the occupancy loads to the vertical load resisting system (either a frame or load bearing walls). It may or may not act as a diaphragm.

CODE	
1	Plywood on wood joists (either full span or on additional secondary and primary supports of steel or wood)
2	Light weight (2in) tongue and groove on wood joists(possibly with additional frame support)
3	Heavy tongue (3in) and groove on wood joists
4	Tongue and groove on 'semi-mill' wood members
5	Tongue and groove on light timber beams
6	Tongue and groove on heavy timber beams NOTE: The term 'plank' is more commonly substituted for tongue and groove
7	Lightweight concrete fill over plywood
8	Poured-in-place reinforced concrete flat plate
9	Poured-in-place reinforced concrete one-way slab
10	Poured-in-place reinforced concrete two-way slab
11	Precast reinforced cocnrete slab (including lift slabs)
12	Precast prestressed concrete slab
13	Post-tensioned concrete slab
14	Reinforced gypsum concrete slabs (either precast or poured-in-place)
15	Structural steel joists with concrete slab
16	Structural steel joists with precast concrete elements
17	Structural steel beams with concrete slab
18	Concrete fill on metal decking
19	Structural steel truss
20	Masonry arch
21	Unknown

Table 7-3. Roof Construction

The roof construction is that part of the load bearing structure which is, or supports, the external upper covering of the building. It does not include any separately applied roof covering.

CODE	
1	Light timber rafters with plywood or plank sheathing
2	Light timber rafters without sheathing
3	Light timber beams, joists or spandrels with sheathing
4	Light timber beams, joists or spandrels without sheathing
5	Heavy timber beams or joists
6	Poured-in-place reinforced concrete flat plate
7	Poured-in-place reinforced concrete one-way slab
8	Poured-in-place reinforced concrete two-way slab
9	Precast reinforced concrete slab (including lift slabs)
10	Precast prestressed conrete slab
11	Post-tensioned concrete slab
12	Reinforced gypsum concrete slabs (either precast or poured-in-place)
13	Structural steel joists with concrete slab
14	Structural steel joists with precast concrete elements
15	Structural steel beams with concrete slab
16	Structural steel truss
17	Metal truss (non-steel)
18	Steel frame
19	Metal frame (non-steel)
20	Concrete fill on metal decking
21	Masonry arch
22	Thin concrete shell
23	Light timber truss
24	Unknown

Table 7-4. Exterior Wall Construction

The exterior wall as used here is that element of the building's structure which encloses the building on its external circumference and which is capable of supporting itself or of providing a primary or secondary load path. It does not include any type of non-load-bearing covering such as shingles, light siding, or veneer.

CODE	
	MASONRY
1	Unreinforced hollow unit masonry
2	Reinforced hollow unit masonry
3	Unreinforced solid unit masonry
4	Reinforced solid unit masonry
5	Unreinforced cavity wall masonry
6	Reinforced cavity wall masonry
7	Glass block masonry
8	Stone masonry
	CONCRETE
9	Precast reinforced concrete walls (i.e., tilt-up walls)
10	Poured-in-place reinforced concrete walls
11	Poured-in-place unreinforced concrete walls
	METAL
12	Aluminum or steel sheeting (when load carrying)
13	Insulated metal panel walls of sandwich construction
	WOOD OR STUCCO
14	Wood or plywood sheathing
15	Stucco
	OTHER
16	None (as might be the case for a steel frame building with non-load carrying sheet metal siding)
17	Unknown

Table 7-5. Interior Wall Construction

The interior walls are those building elements which subdivide the interior space of the building. For classification purposes, they must be full height but they need not be load bearing.

CODE	
1	Unreinforced masonry
2	Reinforced masonry
3	Unreinforced conrete
4	Reinforced concrete
5	Glass block masonry
6	Gypsum masonry
7	Stone masonry
8	Wood frame with plywood, fiberboard, or particleboard sheathing
9	Wood or metal studs with lathe and plaster or gypsum board
10	Metal
11	Adobe
12	No interior walls
13	Unknown

Table 7-6. Equivalent Building Relationships

RISK MITIGATION METHODOLOGY BUILDING CATEGORIES	EQUIVALENT BUILDING CATEGORIES BASED ON BUILDING INSPECTION FORM INFORMATION	
	VERTICAL AND LATERAL LOAD RESISTING SYSTEM	EXTERIOR WALL CONSTRUCTION
FIRE HAZARD		
• FIRE • NON-COMBUSTIBLE • ORDINARY OR WOOD FRAME	NO CONVERSION NECESSARY BECAUSE "CONSTRUCTION TYPE" FOR FIRE SEPARATELY SPECIFIED ON BUILDING INSPECTION FORM	
FLOOD HAZARD		
• WOOD FRAME	23-27, 29	NOT USED
• MOBILE HOMES	28	
• OTHER	1-22	
EARTHQUAKE HAZARD		
• STEEL MOMENT RESISTING FRAME	16, 18	NOT USED
• CONCRETE MOMENT RESISTING	11, 15	
• STEEL BRACED FRAME	17, 19, 20, 22	
• CONCRETE BRACED FRAME	12, 13	
• SHEAR WALL	8-10	
• FRAME AND SHEAR WALL	14, 21, 23-25	
• WOOD SHEAR WALL	26	
• BEARING WALL	1-7, 27, 29	
• MOBILE HOME	28	
WIND HAZARD		
• WOOD FRAME	23-26	—
• CONCRETE OR MASONRY WALL	1-7, 27, 29	—
• METAL	16-18, 20, 19, 21,22	12
• DUCTILE STEEL FRAME	16-18, 20	EXCEPT 12
• CONCRETE OR MASONRY WITHOUT SHEAR WALL OR DUCTILE FRAME	10	—
• CONCRETE OR MASONRY WITH SHEAR WALL OR DUCTILE FRAME	8, 9, 11-15	—
• MOBILE HOME	28	—

8. COST DATA

8.1 Introduction

The acquisition of cost data for implementing various mitigations is a necessary step in the development of an optimum captial investment program. Various sources have been used here to provide this information. These inlcude the "Military Construction Cost Engineering Data" (1973), the Building Construction Cost Data (1977), the Building Cost File/Western Edition (1972), SEAOC Annual Proceedings (1970), and reports by Leslie (1972), the Army Corps of Engineers (1975); and the Federal Insurance Administration (1976). [References 8-1, 8-2, 8-3, 8-4, 8-5, 8-6, 8-7, 8-8.]

Since these cost data are representative of local regions, geographic cost factors are provided so that these estimates can be applied to other areas. Table 8-1 provides factors for the continental United States. Figure 8-1 displays the cost factors for the conterminious United States in map form. All cost estimates include the cost of labor as well as the cost for materials.

It must be recognized that in a general methodology such as this one, only very general classes of mitigations can be considered. Consequently, only a crude cost estimate can be provided. Thus, once a set of mitigations are recommended by the methodology, a detailed engineering evaluation of their feasibility and actual cost must be made.

Table 8-1. Geographic Cost Factors Continental United States [8-1]

* CANNOT BE USED WHERE STATUTORY LIMITS APPLY.

STATE	EXCEPTIONS	EFD	INDEX
ALABAMA		SOUTH	.89
	GULF COAST AREA		.99
ARIZONA		WEST	1.01
	*TUSCON, YUMA P.G. & DAVIS-MONTHAN AFB, *PHOENIX		1.10
	FT. HUACHUCA		1.20
	GILA BEND AFS		1.15
ARKANSAS		SOUTH	.89
CALIFORNIA		WEST	1.06
	*SUNNYVALE, SAN FRANCISCO BAY AREA, DESERT AREAS AND SIERRA ARMY DEPOT, *EDWARDS, *GEORGE AFB		1.14
COLORADO		NORTH	1.01
CONNECTICUT		NORTH	1.08
DELAWARE		NORTH	1.02
DISTRICT OF COLUMBIA		CHES	1.00
FLORIDA		SOUTH	.90
	KEY WEST, *CAPE KENNEDY, *PATRICK AFB		1.15
	MIAMI		1.02
GEORGIA		SOUTH	.92
IDAHO		WEST	.96
	MT. HOME AFB		1.20
ILLINOIS		NORTH	1.05
	SCOTT AFB & GRANITE CITY ARMY DEPOT		1.20
INDIANA		NORTH	1.01
	GRISSOM AFB		1.10
IOWA		NORTH	.99

Table 8-1. Geographic Cost Factors Continental United States (Continued)

* CANNOT BE USED WHERE STATUTORY LIMITS APPLY.

STATE	EXCEPTIONS	EFD	INDEX
KANSAS		NORTH	1.00
	*FORBES AFB, *MC CONNELL		1.05
KENTUCKY		LANT	.97
	*FORT KNOX		1.05
LOUISIANA		SOUTH	.90
	FT. POLK, *NEW ORLEANS		1.05
MAINE		NORTH	.91
	*FAR NORTHERN AREA		1.10
MARYLAND		CHES	.99
	*BAINBRIDGE, *CHELTENHAM, *ANDREWS AFB		1.05
	FT. RITCHIE, PATUXENT RIVER ATC		1.10
MASSACHUSETTS		NORTH	1.07
	FT. DEVENS		1.15
	*NANTUCKET		1.65
	*HANSCOM AFB, *OTIS AFB		1.10
MICHIGAN		NORTH	1.11
	NORTHERN AREA		1.20
MINNESOTA		NORTH	1.04
	NORTHERN AREA		1.15
MISSISSIPPI		SOUTH	.87
MISSOURI		NORTH	.98
	ST. LOUIS, *WHITEMAN AFB		1.04
	FT. LEONARD WOOD		1.20
MONTANA		WEST	.93
	NORTHERN AREA		1.15
NEBRASKA		NORTH	.95
NEVADA		WEST	1.06

Table 8-1. Geographic Cost Factors Continental United States (Continued)

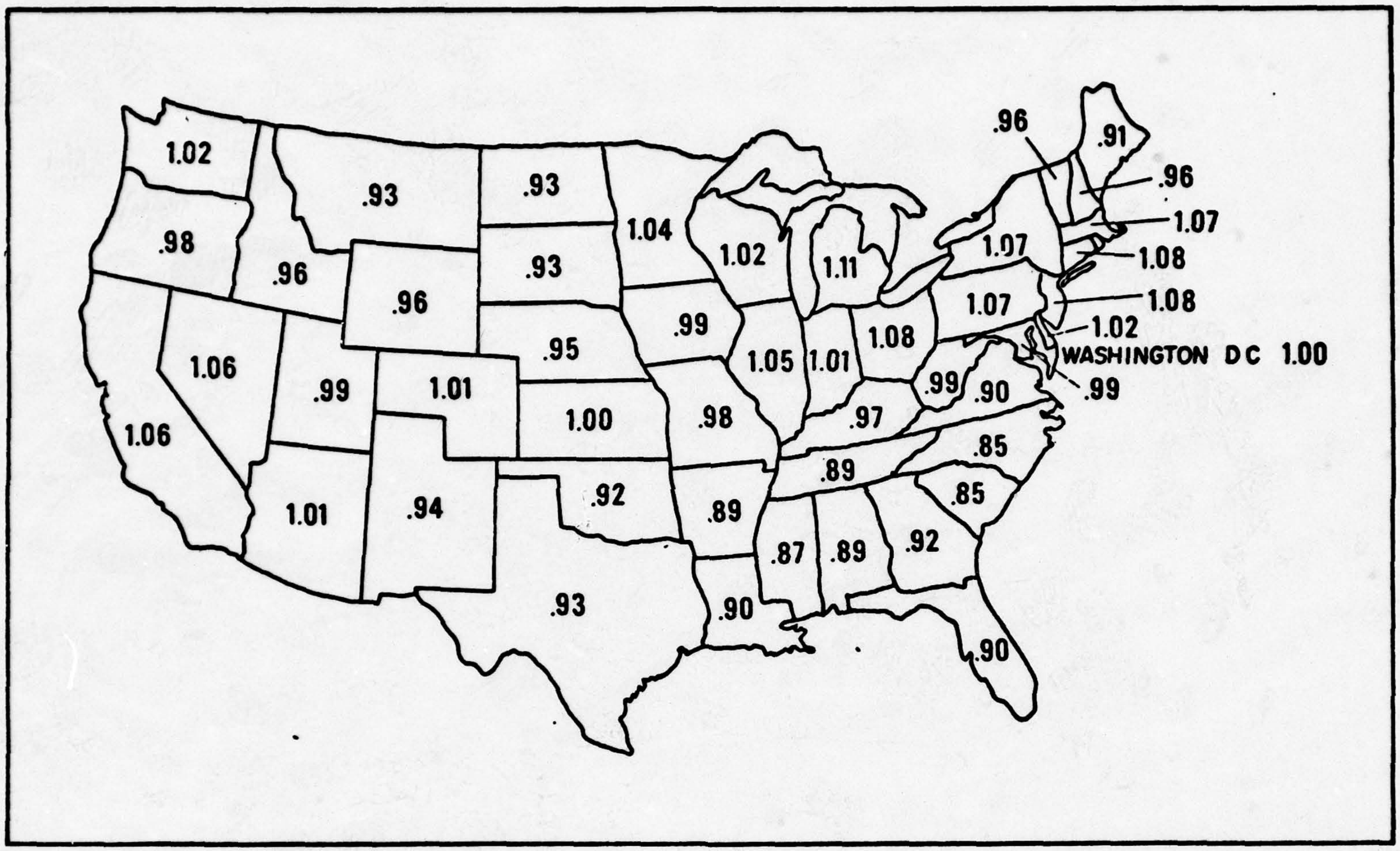
* CANNOT BE USED WHERE STATUTORY LIMITS APPLY.

STATE	EXCEPTIONS	EFD	INDEX
NEW HAMPSHIRE		NORTH	.96
NEW JERSEY		NORTH	1.08
	*NEWARK AREA, *MC GUIRE AFB		1.15
NEW MEXICO		SOUTH	.94
NEW YORK		NORTH	1.07
	NEW YORK CITY AND LONG ISLAND		1.20
	*WEST POINT		1.30
NORTH CAROLINA		SOUTH	.85
	CHERRY POINT & CAMP LEJEUNE		1.00
NORTH DAKOTA		NORTH	.93
	NORTHERN AREA		1.15
OHIO		NORTH	1.08
	CLINTON COUNTY AFB, WRIGHT-PATTERSON AFB		1.20
OKLAHOMA		SOUTH	.92
OREGON		WEST	.98
	CONDON AFB		1.15
PENNSYLVANIA		NORTH	1.07
	*PITTSBURG, *PHILADELPHIA		1.10
RHODE ISLAND		NORTH	1.04
SOUTH CAROLINA		SOUTH	.85
	CHARLESTON, FT. JACKSON, SHAW AFB		1.00
SOUTH DAKOTA		NORTH	.93
	ELLSWORTH AFB		1.15
TENNESSEE		SOUTH	.89
	*ARNOLD ENG. DEV CTR		.95

Table 8-1. Geographic Cost Factors Continental United States (Continued)

* CANNOT BE USED WHERE STATUTORY LIMITS APPLY.

STATE	EXCEPTIONS	EFD	INDEX
TEXAS		SOUTH	.93
	*MATAGORDA ISLAND		1.05
UTAH		WEST	.99
	DUGWAY PROVING GROUNDS		1.20
	HILL AFB		1.05
VERMONT		NORTH	.96
VIRGINIA		LANT	.90
	AREA ADJACENT TO D.C., NORFOLK-NEWPORT NEWS AREA, DISMAL SWAMP AREA, FT. LEE & DAHLGREN	CHES	1.00
WASHINGTON STATE		WEST	1.02
	PUGET SOUND AREA		1.15
WEST VIRGINIA		LANT	.99
	*SUGAR GROVE		1.05
WISCONSIN		NORTH	1.02
WYOMING		NORTH	.96



77-1230

Figure 8-1. Map of Continental United States showing Geographic Cost Factors [8-1]

8.2 Fire Mitigation Cost Data

Cost estimates are provided in Table 8-2 for the following fire mitigations:

- installation of an automatic fire detection system,
- installation of an automatic fire sprinkler system,
- fireproofing.

Table 8-2. Fire Mitigation Cost Data [8-1, 8-2]

MITIGATION		COST (1975)
		DOLLAR/FT^2 OF BUILDING
AUTOMATIC DETECTION SYSTEM		1.18
AUTOMATIC SPRINKLER SYSTEM		
AGE	CAPACITY (HEADS)	DOLLAR/HEAD
PROPOSED BLDG	20 - 500	74.62
	501 - 2000	67.84
	> 2000	63.32
EXISTING BLDG	20 - 500	78.02
	501 - 2000	73.50
	> 2000	67.84
		DOLLAR/FT^2 OF SURFACE AREA
FIREPROOFING (4 HR FIRE RATING)		0.74

The cost for the detection system assumes a 500-ft connection to an active alarm system. The cost of the installation is independent of whether the system is put in with the initial

construction or after the building has been erected. The cost of installing an automatic sprinkler system depends on whether it is an existing or proposed structure. The costs are higher for the existing structure. In addition, the cost per sprinkler head decreases when more heads are installed. The cost of fireproofing assumes that a fire rating for four hours is obtained.

All of these cost estimates were obtained from either MCCED [8-1] or BCF [8-3] and have been converted to 1975 dollars when necessary.

8.3 Wind Mitigation Cost Data

Cost estimates are provided in Figures 8.3 and 8.4 for designing or modifying the following structural classifications to the respective design levels:

STRUCTURAL CLASSIFICATION	STRUCTURAL DESIGN LEVEL
One- to Three-Story Residential Wood Frame	0.75, 1.0, 1.5, 3.0 UBC
One- to Three-Story Residential Concrete or Masonry	0.75, 1.0, 1.5, 3.0 UBC
One- to Three-Story Commercial Wood Frame	0.75 UBC
One- to Three-Story Commercial Concrete or Masonry	0.75 UBC
One- to Three-Story Commercial Metal (non-steel)	0.75 UBC
Four or More Stories, Concrete or Masonry	0.75 UBC
Four or More Stories, Concrete Shear Wall	0.75 UBC
Steel Frame, regardless of height	0.75 UBC
Mobile Home	UBC

The cost estimates were derived from those presented for earthquake (Figures 8-5 and 8-6) using the following relationship (Figure 8-2):

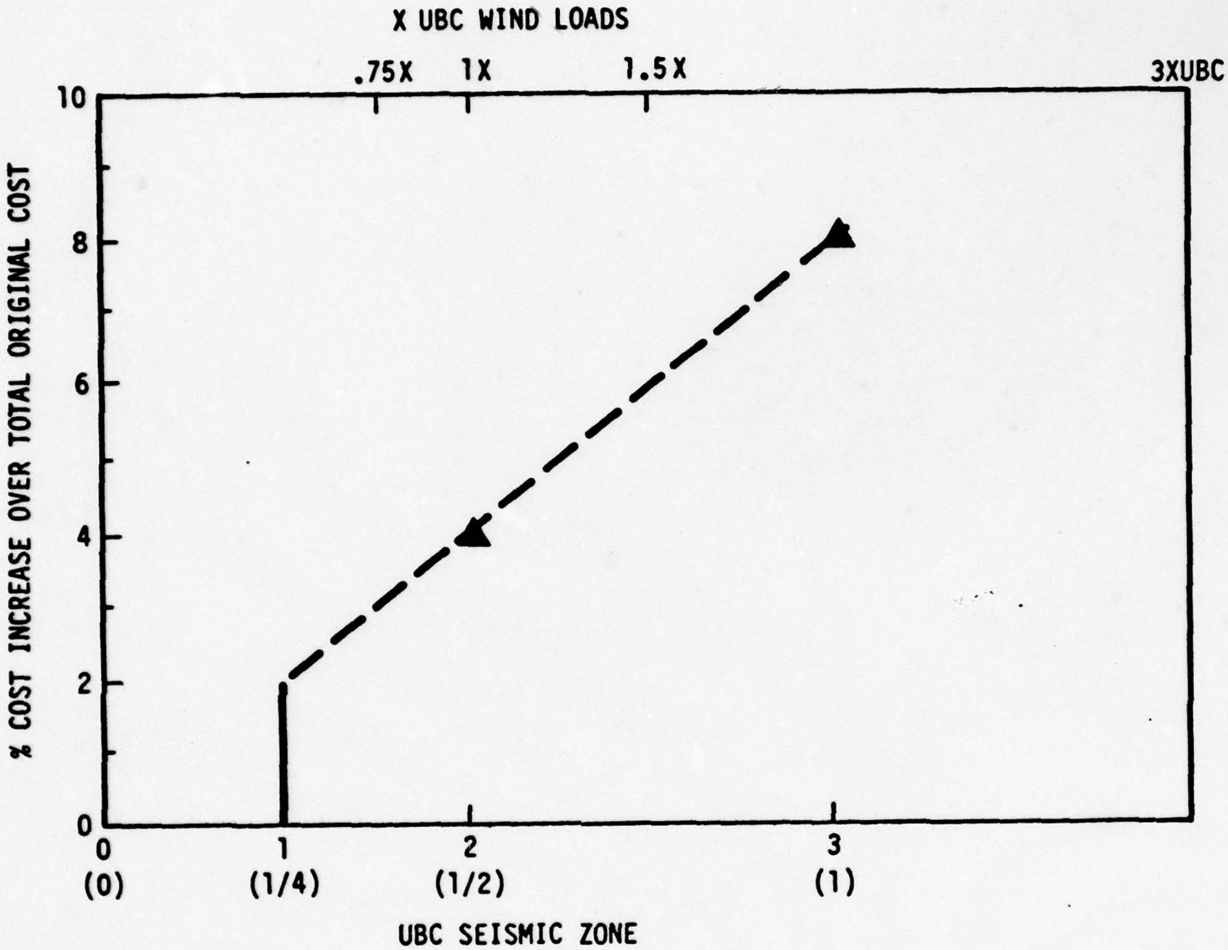


Figure 8-2.

This figure corresponds to Figure 8-5 in Section 8.4. It represents the percent cost increase in designing a one- two- or three-story brick or concrete block building to the various design levels. The data points (represented by ▲) were taken from Reference 8-4. The data point for seismic

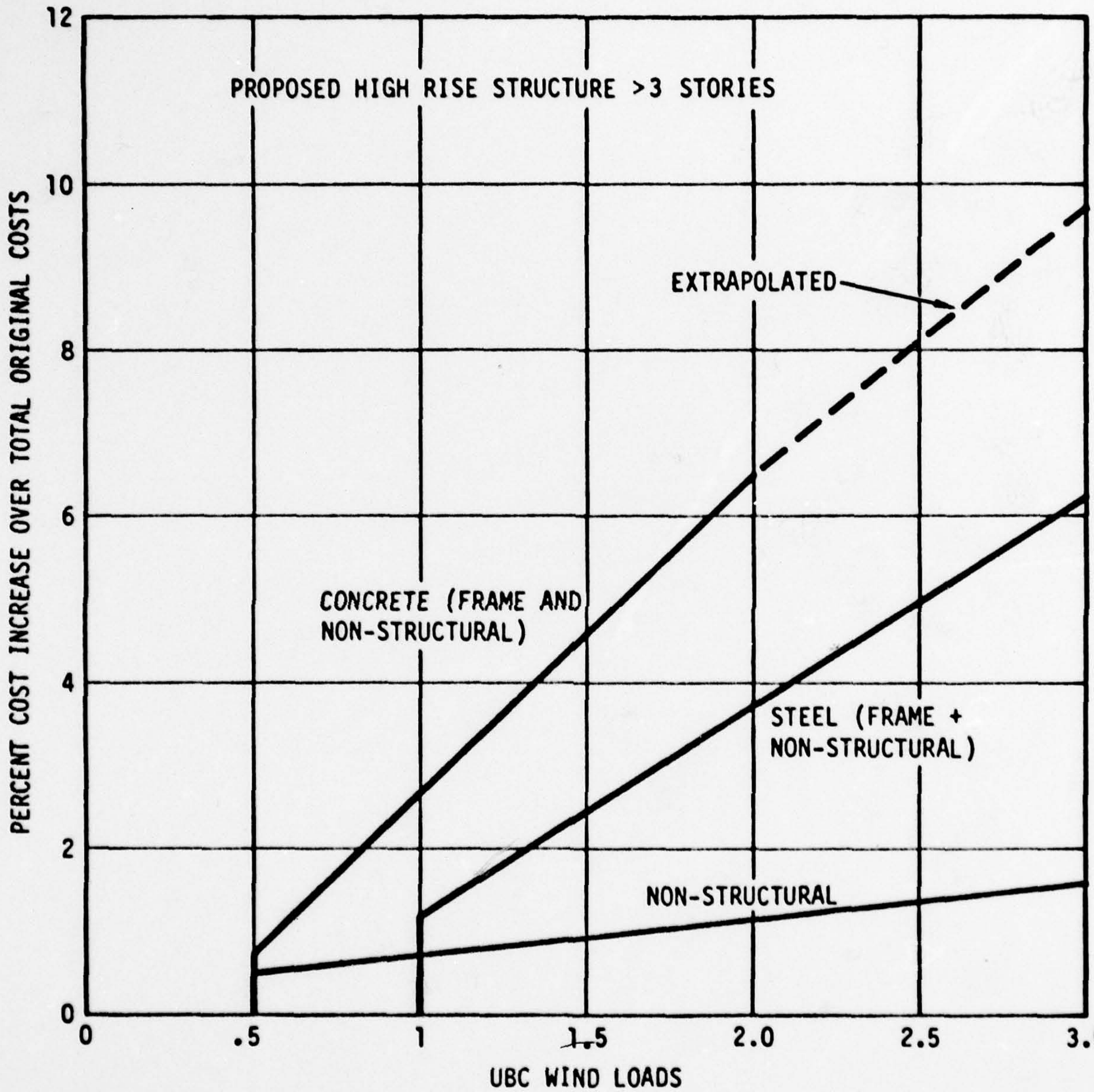


Figure 8-3. Wind Cost Data - High Rise

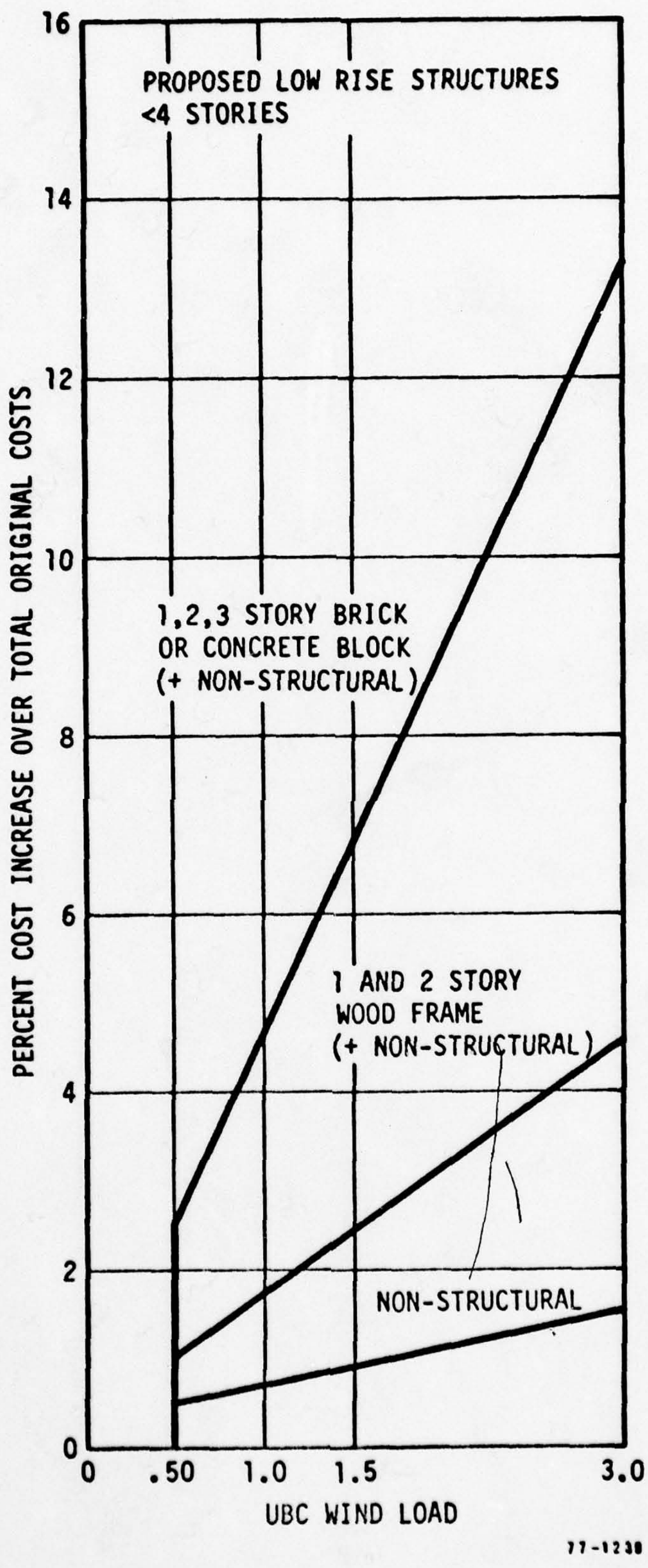


Figure 8-4. Wind Cost Data - Low Rise

Zone 2 cost was developed under the assumption that for areas located in Zones 0, 1, and 2, the percent increase over the original cost is 4 percent (assuming that earthquake regulations are not currently being enforced). The point for Seismic Zone 3 cost was developed under the assumption that for areas which do not presently enforce the UBC design for hurricane, cyclone, tornado, abnormally high winds, or earthquake, the percent increase over the original cost to meet Zone 3 requirements would be 8 percent. If the area does enforce the UBC design requirements for wind, then the increase to meet Zone 3 requirements is only 4 percent. Therefore, using the previous information, one can construct an upper absissa scale (Figure 8-4) that would correspond to UBC wind loads. Since a structure currently designed for UBC level wind resistance requires a 4 percent increase to meet Zone 3 requirements, one can correspond the UBC design wind loads to seismic Zone 2. The other UBC wind loads (i.e., 0.75, 1.5 and 3.0) were obtained by scaling the values on the upper absissa. This relationlship between wind load and seismic zone was used to determine the wind cost factors from the earthquake cost factor.

As with earthquake, the percent increase for a proposed building is multiplied by 8 to get the cost (as a function of replacement value) of modifying an existing building.

The cost of anchoring a mobile structure was found to be approximately $500 per unit from a telephone survey of several mobile home dealers.

The cost to strengthen windows for wind loading was found to be $0.62 per square foot [8-3, p. 132].

8.4 Earthquake Mitigation Cost Data

Cost estimates are provided in Figures 8-5 and 8-6 for the following earthquake mitigations:

- modifying or designing structural and non-structural systems to UBC Level 1
- modifying or designing structural and non-structural systems to UBC Level 2
- modifying or designing structural and non-structural systems to UBC Level 3
- modifying or designing structural and non-structural systems to UBC Level S
- modifying or designing non-structural system to UBC Level 1
- modifying or designing non-structural system to UBC Level 2
- modifying or designing non-structural system to UBC Level 3
- modifying or designing non-structural system to UBC Level S

Figure 8-5 provides estimates for proposed existing high-rise structures while Figure 8-6 gives estimates for proposed low-rise structures. These estimates represent the percent increase over the total original costs. For high-rise structures, estimates are provided for reinforced concrete structures (frame + non-structural) and steel structures (frame + non-structural). For low-rise structures, costs are given for one-, two- or three-story brick or concrete block buildings (frame + non-structural) and one- and two-story wood-frame buildings (frame + non-structural). The source for the high-rise estimates was Leslie [8-5]; the source for the low-rise estimates was the SEAOC Proceedings [8-4].

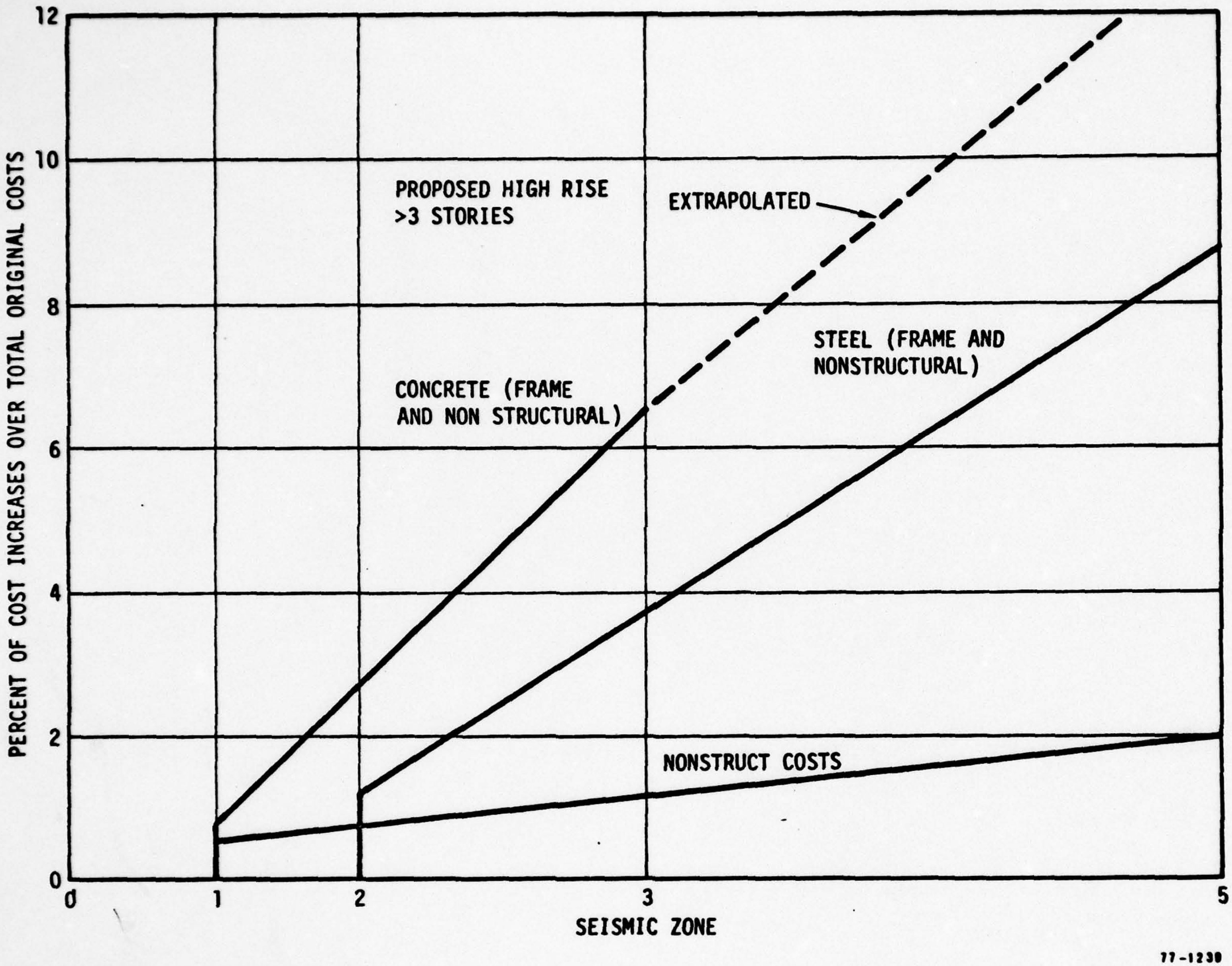


Figure 8-5. Earthquake Cost Data - High Rise [LESLIE, 1972]

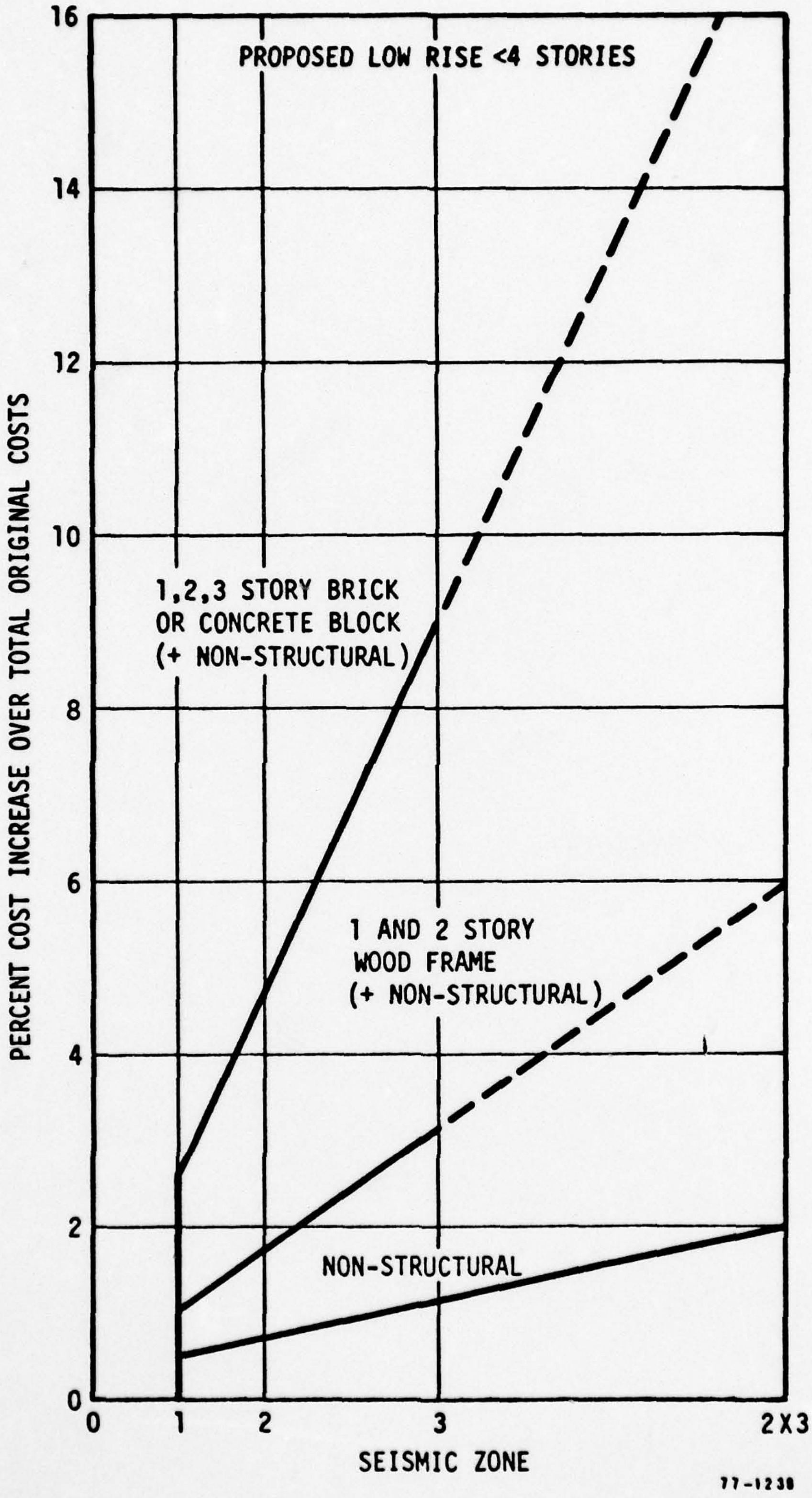


Figure 8-6. Earthquake Cost Data - Low Rise [SEAOC, 1970]

Since the cost of modifying an existing structure to the foregoing levels is considerably higher than that for a proposed structure, the percent increase is multiplied by a factor of 8 to obtain cost factors for existing structures. Therefore, all cost curves in Figures 8-5 and 8-6 are for proposed buildings.

8.5 Flood Mitigation Cost Data

The cost data incorporated into this methodology for flood mitigations are summarized in Figures 8-7 through 8-9. These figures are a very rough approximation of data provided in References 8-6 through 8-8. The data presented here are for buildings of a specific size. It is assumed that the costs will vary linearly with building area or perimeter, as appropriate.

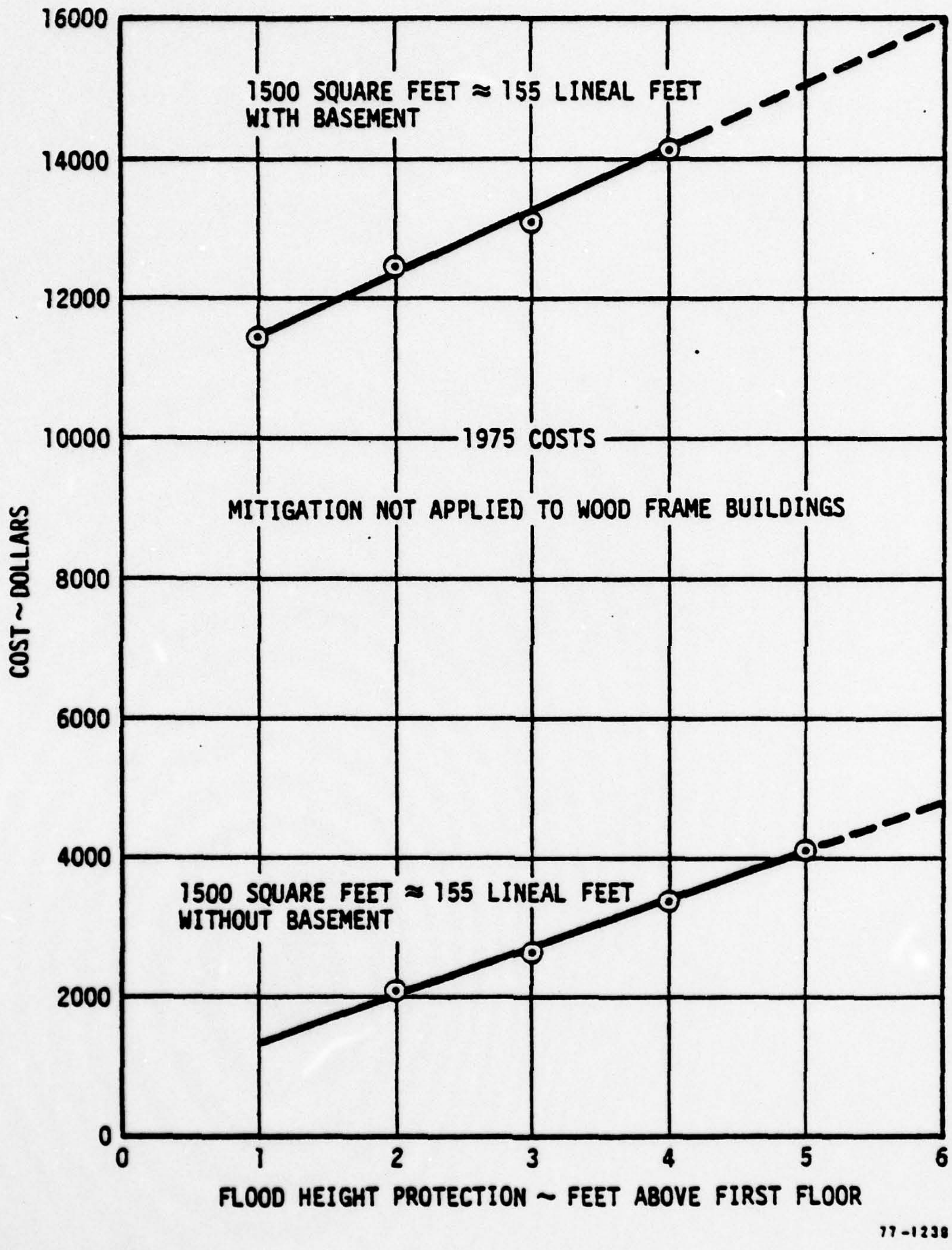


Figure 8-7. Floodproofing to Exclude Water - Residential [8-6]

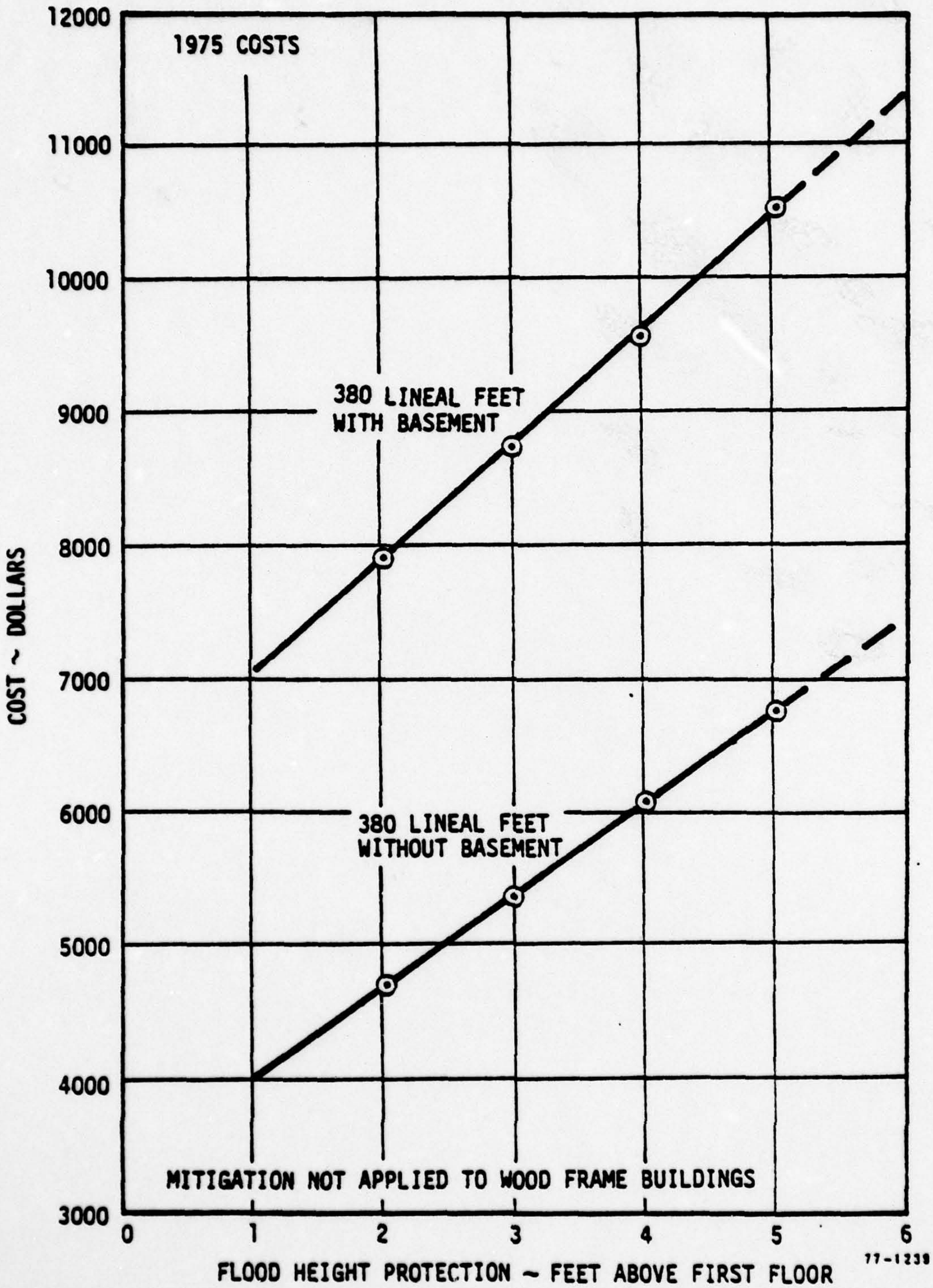


Figure 8-8. Floodproofing to Exclude Water - Commercial [8-6]

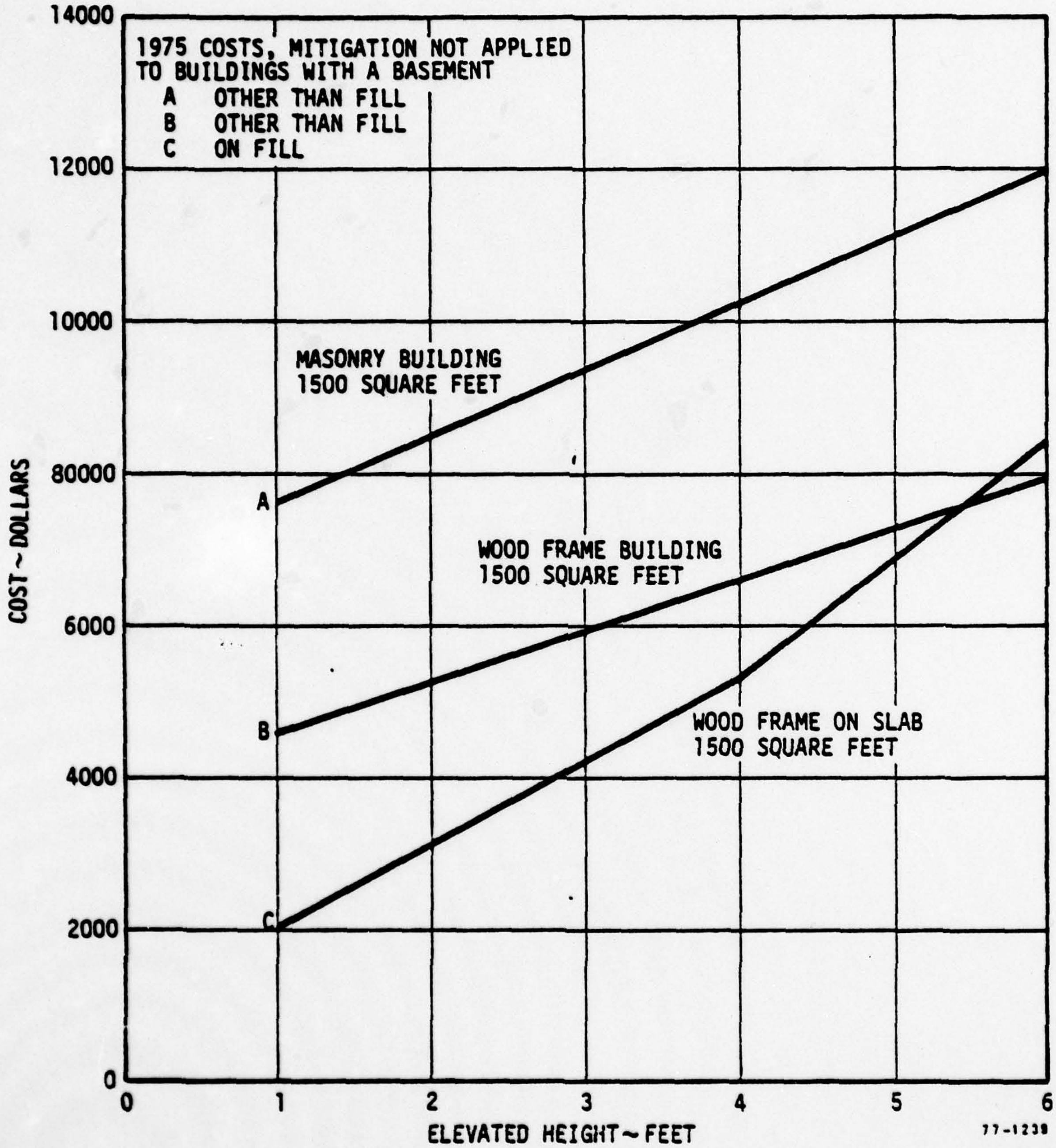


Figure 8-9. Elevating Building [8-7, 8-8]

8.6 References

8-1 Naval Facilities Engineering Command, "Conceptual Military Construction Cost Engineering Data," NAVFAC p. 448, December 1973.

8-2 R. S. Godfrey, Ed. in Chief, Building Construction Cost Data, 1977, 35th Edition, R. S. Means Co., 1977.

8-3 Construction Publishing Company, Building Cost File, 1972.

8-4 SEAOC, "Report of the Ad Hoc Committee on Cost of Design for Earthquake," O.S.T. Task Force on Earthquake Hazard Reduction, San Francisco, September 1970.

8-5 S. K. Leslie, and J. M. Biggs, "Earthquake Code Evaluation and Effects of Seismic Design on the Cost of Buildings," Seismic Design Decision Analysis Report No. 2, MIT-CE-R72-20, Mass. Inst. of Tech., May 1972.

8-6 W. D. Carson, "Estimating Costs and Benefits for Non-structural Flood Control Measures," The Hydrologic Engineering Center, U. S. Army Corps of Engineers.

8-7 Federal Insurance Administration, "Elevated Residential Structures - Reducing Flood Damage Through Building Design: A Guide Manual," U. S. Department of Housing and Urban Development, 1976.

8-8 The Hydrologic Engineering Center, "Costs of Placing Fill in a Flood Plain," U.S. Army Corps of Engineers, May 1975.

9. UNCERTAINTY

The effect of uncertainty on the optimum mitigation sequence can be considered using a "Monte Carlo" approach. The overall structure of this program is presented in Figure 9-1. The first operation consists of the random selection of the damage algorithms (i.e., mean number of events per year) for each of the four hazards. The program then proceeds to determine the optimum series of mitigations as previously described. When this sequence of operations is completed, another set of damage algorithms are randomly selected, and the entire process repeated. Thus, each "Monte Carlo" sample will produce a complete analysis of the subject facility. Each set of results will be saved on a special data file. When the required number of "Monte Carlo" samples have been run, the data files will be interrogated to determine which mitigation was most often chosen first, which second, and so forth. The resulting sequence of mitigations thus will incorporate not only the basic hazard, exposure, damage and vulnerability models, but also the effect of uncertainty in our definition of both the damage algorithms and the hazard models.

The random selection of the damage algorithm will be constrained by the means and variances of these parameters as determined from the literature, or by independent study. For example, a particular damage matrix for fire can be represented as follows by using the data developed from our survey of naval fire experts:

Fire Protection	= None
Construction Type	= Non-Combustible
Interior Finish	= Combustible
Fire Load	= Moderate

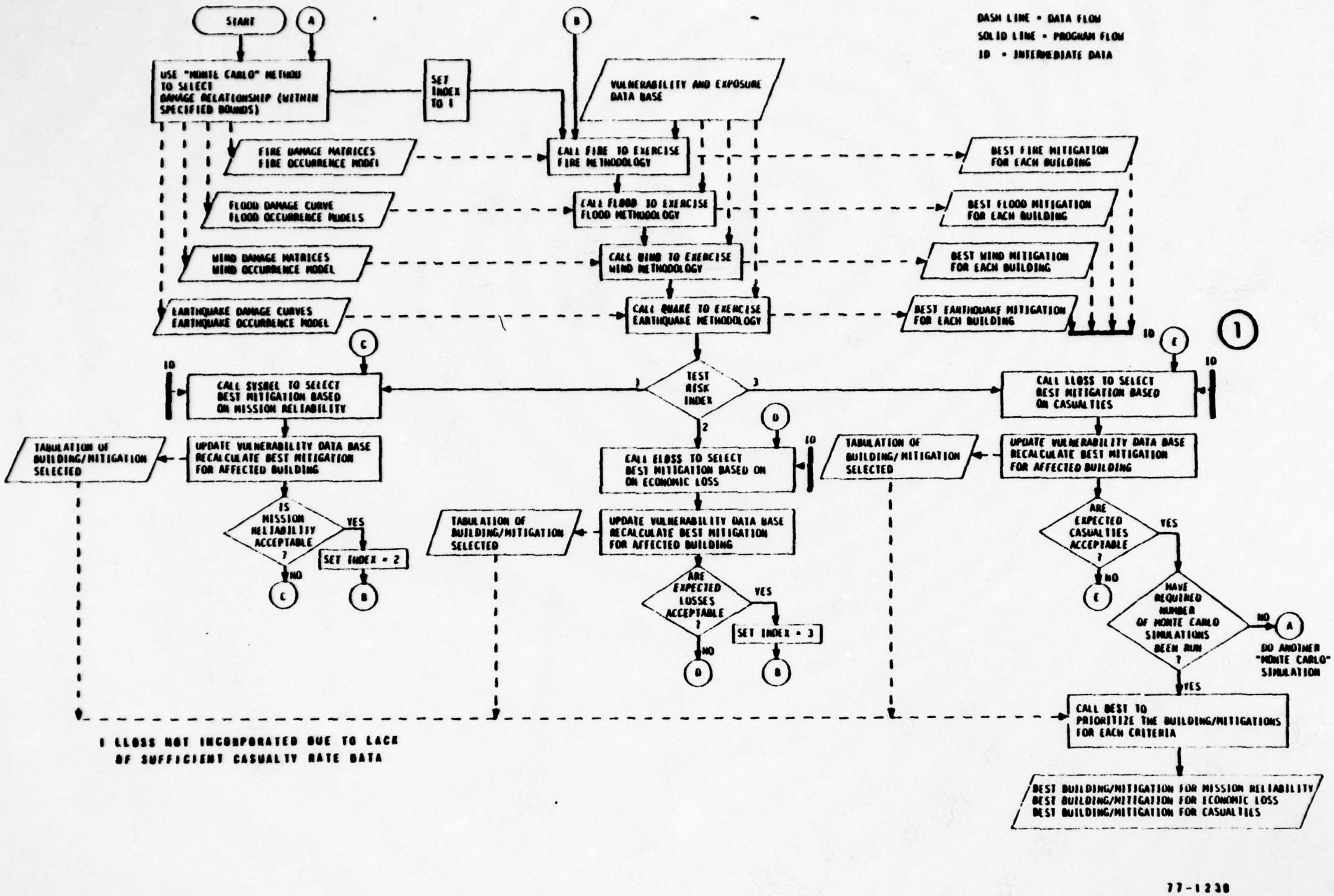


Figure 9-1. General Methodology Considering Uncertainty in Models

AD-A073 157 WIGGINS (J H) CO REDONDO BEACH CALIF F/G 13/13
CAPITAL INVESTMENT PROGRAM FOR MITIGATION OF RISKS FROM NATURAL--ETC(U)
MAY 77 L T LEE, R T EGUCHI, J COLLINS N00025-75-C-0014
UNCLASSIFIED TR-77-1239-1 NL

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Damage State i	Damage Matrix Probability x_i	Variance of Probability y_i
1	0.42	0.058
2	0.20	0.012
3	0.19	0.023
4	0.09	0.006
5	0.10	0.053
SUM	1.00	

The selection procedure will be such that when 100 x_1 have been selected, the variance of that sample will be approximately y_1.

Not only are the Damage Probability Matrices randomly perturbed, as shown above, but the Central Damage Ratio for each damage state are also perturbed. This is done under the assumpution that the damage follows a log-normal distribution in all cases, that the Central Damage Ratios reported herein are mean values, and that (unless indicated otherwise) the coefficients of variation are 0.25.